SEVENTH MILITARY-INDUSTRY MISSILE AND SPACE RELIABILITY SYMPOSIUM

18-21 JUNE 1962

NAS NORTH ISLAND
SAN DIEGO, CALIFORNIA

Sponsored By

THE OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

In Cooperation With

ARMY · NAVY · AIR FORCE · NASA

Host Agency

BUREAU OF NAVAL WEAPONS

496

Code 1

NASA CR-50,104

PREFACE

The enclosed papers are those presented at the SEVENTH MILITARY-INDUSTRY MISSILE AND SPACE RELIABILITY SYMPOSIUM held at the Naval Air Station, North Island, San Diego, California on 18-21 June 1962.

This conference was sponsored by the Office of the Director of Defense Research and Engineering in cooperation with U. S. Army, U. S. Air Force, U. S. Navy and NASA. The Bureau of Naval Weapons acted as host agency.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

KEYNOTE ADDRESS BY
GENERAL B. A. SCHRIEVER
SEVENTH MILITARY-INDUSTRY MISSILE AND
SPACE RELIABILITY SYMPOSIUM
SAN DIEGO, CALIFORNIA

MANAGEMENT -- THE KEY TO ACCOMPLISHMENT

It gives me great pleasure to be with you this morning. The symposium this week is a welcome chance to tackle specific reliability problems--and to come up with some solutions. The exchange of ideas is always valuable, and I am confident this meeting will lead to even greater teamwork between military and industry on problems of mutual concern.

I am certain that I do not have to convince you of the importance of reliability. If you are not convinced already, no words of mine could persuade you. Nevertheless, it may be helpful to look at the increasingly urgent requirements for dependability in modern aerospace systems.

In recent years it has become clear that performance has outstripped reliability in a number of areas. This imbalance needs to be corrected. Overall systems effectiveness implies considerably more than performance. In the past, performance has received the lion's share of our attention. It has leaped ahead in a spectacular fashion, while reliability has been hidden away in a lump of things called "just good engineering."

But as our missions become more sophisticated and hardware grows more complex, reliability becomes a primary consideration. It becomes a design parameter like size, weight, speed, and accuracy. To put it in another way, we do not consider that we have a weapon system--until we have a reliable one.

- - - FORGING MILITARY SPACEPOWER - - -

The requirements of our national security make this point obvious. In a credible deterrent force, operational readiness is fully as important as mission profile capability. We can make predictions of probable losses due to enemy action. It is equally important to predict probable failures due to unreliability.

Reliability problems are complicated by the fact that missile systems must not only be capable of long storage; they must also be capable of quick response. This combination imposes extremely high demands for reliability in systems, sub-systems, and components. If a missile cannot be launched when it is needed, then we would be better off without it.

As space missions become a larger part of our program, the demand for reliability increases at a tremendous rate. Space systems are growing in complexity. They are required to operate in a new environment which we have yet to completely understand. They will be required to operate for exceedingly long time periods without maintenance. We must approach infinity in reliability of space systems.

Cost--in both time and money--is also a major consideration. The failure of a single component does not affect just that one part. It may cause the failure of an entire system, with a resulting loss of millions of dollars. Moreover, failures at a critical point in development can cause delays of weeks or months in a program of great national importance. For manned space systems, the cost of unreliability runs even higher.

All of these factors have caused us to direct our attention to the specific reliability requirements of missile and space systems. We can no longer afford to take the easy view that reliability is something that "just happens." It must be planned for and worked for--in a careful, organized, and systematic manner. In systems acquisition today, reliability is more than just a technical problem--it is a definite responsibility of management.

The Air Force, which is a major customer for missile and space systems, has taken a number of specific actions to improve management in this vital area. In my Command we have attacked the reliability problem on a broad front, aiming at both short and long term solutions.

A reliability office in my Headquarters coordinates our efforts. Similar offices are set up in each of our four development divisions and in the three contract management regions. Representatives from each of these offices serve on our Reliability Task Force, a group established more than two years ago as a focal point for Command-wide action in this area.

The basis for attack on unreliability is adequate knowledge by management of the specific problems that exist in each stage of system acquisition. As a means of analyzing the progress made toward establishing goals, we publish a semi-annual "Reliability Status Summary." This document indicates in detail the problems that have been met in our many programs, and the actions that have been taken to solve them.

Our third step, as customers, is to insure the greatest possible understanding between the Air Force and industry with regard to specific reliability requirements. One action toward improving our mutual understanding was the publication of Military Specification MIL-R-27542, "Reliability Requirements for Aerospace Systems, Sub-systems, and Equipments." This replaces several earlier documents and reduces the number of reliability specifications now in effect. It is now a standard section in all new systems contracts.

A further step toward defining our requirements more precisely is the inclusion of quantitative reliability figures in system inception documents--that is, Specific Operational Requirements (SOR's) Operational Support Requirements (OSR's) and System Package Plans. Last January I sent a letter to our four development divisions directing that "all future systems contracts specify probability of mission success or mean times between failures as requirements in quantitative numerical terms."

This use of specific numerical reliability requirements will provide a basis for more effective controls on trade-offs and reliability expenditures. I am convinced it will substantially accelerate our progress toward systems effectiveness.

Looking at the long term needs in the reliability field, we have focussed our attention on two areas: research, and increased training for our personnel. We visualize an expanded research program that might involve the outlay of several million dollars a year--and bring us savings of many times that amount. It would provide for investigation of a number of promising areas, such as development of better reliability numerical models and prediction techniques; study of accelerated aging and non-destructive testing; mathematical simulation; improvement of incipient failure detection; and study of the environment-reliability relationship.

The adequate training of personnel is just as important as increased research. We are currently taking part in several types of educational programs. Twenty-five USAF officers are enrolled in the first 18-month graduate course at the Air Force Institute of Technology working toward a M.S. degree in reliability engineering.

More than 300 AFSC personnel have completed one-week reliability courses sponsored by professional societies and non-profit institutions. Four hundred AFSC and AFLC personnel have taken a three-week course in reliability that has been established by the Air Logistics School of the Air Force Institute of Technology.

All of these actions are directed toward improving our management capability, and I am certain they will pay off with increased reliability. Already we have seen some highly gratifying results of concentration in this area. The progress of the Minuteman system is a good example. During the past two years we have made a sustained effort to bring some 40 individual electronic components for Minuteman to an entirely new level of reliability. The result has been an increase in reliability of about two orders of magnitude in these components. In other words, on the average they are about a 100 times as reliable as similar components of two years ago.

In the Army and the Navy and throughout the government generally there is a similar strengthening of reliability management. This is essential in acquiring the kind of systems we need. But there is another factor that is equally important to progress in this area. This might be called a matter of attitude.

In this connection, two points need to be stressed. First of all, there seem to be no theoretical limits on reliability. If there are practical limits, we have not yet reached them--and I would not like to predict that we never will. We are aware of apparent limitations today, but many of them may exist only in our imaginations. In recent years we have seen the solution of a variety of supposedly "impossible" problems. Management must never rule out the possibility of new technical breakthroughs.

A second point is that reliability is a basic responsibility of management. In this respect, management needs to recognize at least four principles:

(1) Reliability begins with initial design.

(2) It depends on aggressive management methods of controlling the reliability program.

(3) It must be verified by a test program that takes into account the complete operating environment.

(4) It cannot be separated from other aspects of management such as human engineering, technical training, and personnel turnover.

It is clear that we can greatly improve systems reliability--if we want to badly enough and will accept our management responsibility. Obviously, there will always be problems when we are operating at the limits of technology. But the presence of problems we can't solve should never stop us from dealing with the problems we can solve.

I am hopeful that this symposium will have two results. It should indicate a number of the long-term reliability considerations that will concern us during the next years. And it should point out some of the immediate practical steps that can be taken to increase reliability at this time. Both results will contribute to our common goal--the acquisition of operational systems that can be depended upon to help insure our national security and survival.

I am sure you will have a series of stimulating and fruitful sessions.

Thank you.

SPECIFYING RELIABILITY IN MILITARY CONTRACTS

Maj/Gen O. J. Ritland
Commander, Space Systems Division
Los Angeles, Calif.

I am grateful for this opportunity to talk about reliability specifications. It is a subject of paramount importance in modern weaponry.

The results we have experienced in producing reliable military systems have stemmed directly from the decisions made and support given by the individuals present here today. Yet despite significant progress in the past, we still have a substantial distance to travel in reliability. Of this you are well aware. Therefore, I will not dwell on the importance of reliability, nor direct my remarks in a motivational vein. Instead, I should like to present to you some concrete experience of the Air Force during several years of contracting for reliability in ballistic and space systems.

Today, I plan to discuss the following areas:

Some Basic Reliability Concepts

Brief History of Contractually Specifying Reliability Requirements

Management Requirements

Quantitative Requirements

Control of Piece Parts

Current Trends in Specifying Reliability Requirements

In setting the stage, I would like to consider several basic reliability concepts of importance to my subject. These are:

First: Reliability is one of the major system design characteristics. It is a characteristic which must permeate all technical, cost, schedule, or other management considerations for decision making. There are two distinct complementary methods of attaining reliability; one is through technical development. The other is through management control. Reliability through technical development begins with design assurance, and progresses thru developmental testing and measurement to production control and handling and packaging. As an area of management control, reliability is attained through application of system reliability requirements at all decision making levels, and by rigid, uncompromising enforcement of discipline in every action or decision.

In both approaches reliability cannot be left to chance. It can only be assured through a carefully planned and executed program. It cannot be expected from some significant scientific or engineering breakthrough. It will be accomplished through minute and meticulous attention to detail.

Second: The controls exercised over the selection testing and use of piece parts are proportional to the potential for reliability payoff.

Third: Successful competition for military systems contracts will be increasingly dependent upon a firm's demonstrated capability to produce a reliable product.

Fourth: Qualitative superiority is the key to successful exploitation of space.

These concepts are not new to you. Collectively we have been on a learning curve in the field of missile and space reliability. From lessons learned over the past five or six years we know that we must tailor the "design characteristic" aspect of reliability to the performance requirements of each system and then provide the management controls to attain these requirements. The military services recognized the need to specify reliability requirements in contracts as early as 1956. Early requirements were in the form of clauses oriented toward the technical or "design characteristic" aspect of reliability. One of the first specifications developed and issued by the military was MIL-R-25717 (USAF) "Reliability Assurance Program for Electronic Equipment", 11 January 1959. Subsequently, many specifications, bulletins, and exhibits were published by the services.

As we moved up the reliability learning curve, it became increasingly apparent that there was an urgent need to pull together the various management factors into an integrated requirements package. One of the first documents developed with this objective in mind was Air Force Ballistic Missile Division (AFBMD) Exhibit 58-10, "Reliability Program for Ballistic Missile and Space Systems". That exhibit was incorporated into Ballistic Missile and Space Contracts resulting in a significant impact on the appropriate segments of industry. Shortly thereafter, MIL-R-26674 (USAF) "Reliability Requirements for Weapon Systems", 18 June 1959, was issued by Hq ARDC. This paralleled AFBMD Exhibit 58-10 and was applied to manned aircraft systems.

Subsequently, the best features of these three documents were incorporated into the current specification, MIL-R-27542, "Reliability Program Requirements for Aerospace Systems, Subsystems, and Equipment," published in June of 1961.

With that brief outline of how our basic reliability specification was developed, let us turn to some of the more significant management aspects of an adequate reliability program.

Some of the most formidable problems in the production of reliable systems lie in the management area. An axiom long recognized by the military services is that the inherent reliability of design represents the highest reliability the product has any chance of reaching. Everything that happens downstream of design release, with the exception of design changes, tends to degrade the inherent reliability of design. Therefore, after initial design phase, the major reliability effort should be concentrated in prevention of this degradation. The reliability effort should be organized to provide all the necessary design, service and staff functions and skills to minimize the degradation that may occur during materiel procurement, storage, issue, manufacturing, handling, packaging for shipment, and transportation to the customer.

All of the major functional areas just mentioned are assigned line responsibilities within most companies. A legitimate question might be, why a reliability organization? The reason is obvious. As pointed our earlier, reliability cannot be left to chance. It is a fact of Military and Industrial organizational life that many groups, whose efforts bear directly upon reliability, do not possess the necessary authority and responsibility to achieve reliability. Furthermore, the ever-present demands for more effort in a shorter time span at lower costs can, and often do, influence such groups to slight reliability considerations -- often with subsequent costly results. Unless these weaknesses are overcome, it is virtually impossible to achieve the required level of reliability.

MIL-R-27542, mentioned earlier, establishes minimum requirements that must be followed in planning and organizing a reliability program. Its purpose is to introduce and maintain management visibility into the reliability program to assure that contractual reliability requirements are met. Many of you are familiar with this document. It contains the major requirements which we have found essential to a well conceived reliability program.

The Design Selection Phase of this document sets forth the requirements to be accomplished by a prospective contractor in developing the reliability portion of his proposal. Briefly, this section of the mil spec requires estimates of maximum environmental and stress conditions the system may encounter. This estimate is to be used as the basis for a prediction of achievable reliability during the developmental period. In this phase anticipated problem areas should be identified together with proposed approaches to their solution. A system reliability model with appropriate reliability block diagrams showing the apportionment of reliability over the major subsystems and components is also required.

The prospective contractor must also develop, as a separate section of his proposal, a description of the reliability program to include a detailed listing of specific tasks in a form that permits technical auditing by the government. It is intended that the program plan identify the organizational elements responsible to management for the reliability program and delineate the responsibilities and authority of these elements.

Reliability Program Management requires continuous refinement. The actions necessary for complete systems planning, management, and engineering must be explicitly defined, including the programming and control of reliability activities and a milestone chart showing the timing of every major task. Formal program review points are established to assure that the program remains adequate and that all effort affecting reliability is accomplished as planned.

In accordance with this specification, a reliability program activity status report is required at intervals not to exceed three months. The information submitted will be used for Air Force and contractor management review and program control. This report will contain such information as reliability predictions, status and results of design reviews, actual or potential problems, pertinent test results, and all other data, as mutually agreed to, that would aid in program status assessment.

So far I have discussed the Management Requirements for a Reliability program. I would like to turn now to a discussion of firm quantitative requirements and demonstration procedures. Measurement of any parameter, whether tangible or intangible, requires reference to some standard or base. This applies to reliability just as it does to any other parameter. Admittedly, there are varying degrees of measurement difficulty and relia-

bility, at this point in time, lies far out on the scale of difficulty. It is possible, however, to set forth a firm engineering approach to this measurement problem.

Until we learn to measure or evaluate required reliability efforts, it will be difficult realistically to assign cost to such effort. There are several actions that take place in Air Force Procurement Cycles which require the utilization of quantitative expressions for reliability requirements as a basis for evaluation. These actions include cost estimations, analysis of competitive bids, evaluation of proposals, and evaluation of achieved reliability to determine that contractual requirements have been met. However, the most significant use of quantitative requirements is in the early design considerations of the contractors' engineering efforts.

The design groups should use quantitative requirements in basic design considerations such as reliability apportionment and prediction in parts selection, and in establishing reliability block diagrams. The incorporation of these considerations will be verified through design review and proven through the test program.

In order to aid industry and the government in the proper assessment of the reliability effort, we have been specifying quantitative reliability in contracts for some time. This is the base against which achieved reliability is measured. We believe that the AGREE (Advisory Group on Reliability of Electronics Equipment) Committee was completely right in stating that the best way to arrive at good reliability requirements is to begin with the practice of specifying quantitative reliability requirements.

When quantitative requirements for reliability are specified in contracts, we attempt to augment these requirements with statistically valid demonstration techniques as warranted by the circumstances surrounding the program. We realize, however, that the number of deliverable systems on some programs is insufficient to justify a reliability testing program to prove statistically that quantitative requirements have been met.

Nevertheless, we specify quantitative requirements in such contracts to be demonstrated by alternate methods as may be mutually agreed to by the Air Force and the contractor. For example, reliability performance incentive clauses, where such performance alters the contractor's fee, may be tied to the attainment of these requirements. Some other alternate approaches to reliability demonstration include: (a) the careful and continuing evaluation of the design selection, which is a major basis for developing confidence in the probability of the system meeting its reliability requirements; and (b) insuring every possible use of the available test data from developmental testing to determine the reliability of the system. To aid in this evaluation, reliability program plans must contain specific methods for implementing and documenting the results of design techniques such as reliability apportionment, safety factor analysis, derating procedures, redundancy, failure mode identification and identification and control of critical characteristics of critical parts.

We expect industry to conduct system analysis through development of reliability block diagrams, reliability predictions, parts lists, and to select parts carefully based upon such analysis. Contractors should perform environmental tests to failure, and failure effect analyses. Also, the technique of design review is an invaluable aid.

Another necessary management tool in achieving reliability is a responsive and effective failure correction system.

Industry has taken the lead in developing these techniques. We anticipate that industry will continue to refine existing, and develop new techniques in the future to demonstrate the capability of military systems to meet reliability requirements.

In the specification of reliability requirements, it is to the advantage of industry for government agencies to be as definitive as possible. It is our objective to continue to eliminate vagueness and generality from reliability requirements. We will continue to request that industry does the same.

Turning now to another important reliability management area, one of the most formidable challenges to management is effective controls over the selection and application of reliable piece parts. The Air Force has experienced expensive holds during countdown, aborts, and catastrophic failures traceable to the failure or malfunction of seemingly insignificant piece parts. Items such as semi-conductors, capacitors, resistors, valves, etc., become critical when incorporated into components which, by malfunctioning, can cause failure or serious degradation to accomplishment of flight objectives. This problem became so acute that SSD sent a team of Reliability

personnel out to review the reliability work of several of our space program contractors. Some significant findings resulted from that series of investigations.

This review revealed that one of the primary problems in this area is the lack of adequate piece part military specifications for the space environment. Several members of industry, who were visited by the team had recognized this fact and were either augmenting test and inspection requirements in current military specifications or writing their own specifications.

The team findings in this area merely confirmed that of other groups such as the DOD Ad Hoc Group on "Parts Specification Management for Reliability".

There is a concerted effort under way within the Air Force Systems Command to bring this parts specification problem under control. In order to develop a logical approach to the problem, an AFSC Parts Improvement Group composed of membership from AFSC Divisions, has been formed and has held several meetings. Recommendations have been made by the group, and these will be submitted to the Aerospace Industries Association and the Electronic Industries Association for evaluation and comment prior to further action.

Meanwhile, in order to effect a more immediate interim solution to this problem, the Minuteman Parts Working Group and the Space Parts Working Group of the Ballistic Systems Division and Space Systems Division, respectively, is rapidly developing certain high reliability parts specifications for application to Ballistic Missile and Space Systems. Appropriate members of industry are participating in this effort with the Air Force, and we hope to have the first of these Hi-Rel specs available by July 1962.

In addition to inadequate specifications, the reliability survey team found several management weaknesses which, as corrected, would significantly improve the piece part selection, application and control areas. Typical recommendations for improvement are the following:

First: Each company should maintain a central standards group charged with the responsibility for keeping abreast of the parts field, and for providing assistance to the designers in the selection and application of parts within their systems. Without such centralized control, indiscriminent or uninformed selection and application of parts is inevitable.

Second: The reliability group should be a party to the selection of piece part vendors supplying critical parts. The advice and assistance of the standards group, the reliability group and the design group should be sought in establishing the criteria for receiving inspection and test of piece parts. Suppliers of critical piece parts should be the subject of recurring source inspections to assure that the system of controls in the manufacture of such parts are maintained consistent with the reliability requirements of the system in which the parts are to be used, and to assure that no changes in design or manufacturing processes are made without adequate notification.

Third: There should be an integrated and effective failure reporting, analysis and closed-loop corrective action system to assure that, when failures occur, the cause is determined and corrective action is immediately taken to preclude recurrence. This corrective action system should be established to fit the needs of both the quality and the reliability effort.

Fourth: Critical parts handling is a subject of increasing importance. All contractors must develop parts handling methods consistent with the reliability requirements of the parts.

The foregoing comments on piece parts have emphasized the term "Critical Part." In view of the tremendous number of parts employed in today's system, we believe that the most practical approach to control of these parts is to identify parts in the system where the application of the part is critical to the proper performance of the overall system. After parts for critical applications have been identified, they should be managed in a manner consistent with the criticality.

In this regard the Space Systems Division is now requiring, on new contracts, that the contractor compile a list of critical parts within the system together with his methods of control of such parts and a submission of this list to the appropriate systems program office for review.

At this time I would like to mention some relatively new contract requirements for reliability that the Air Force is either employing or considering for inclusion in future contracts.

Participation in the Interservice Data Exchange Program (IDEP) has, in the past, been voluntary on the part of industry. The benefits that have been derived from this program through elimination of duplicate testing have been significant. The Space Systems Division is now planning to require contractors to participate

in IDEP on a mandatory basis. In addition, IDEP is being expanded through a system called PIDEP (Preliminary Interservice Data Exchange Program). This will require contractors to report their plans for testing with the objective of reducing duplicate test planning efforts.

The Space Systems Division and Ballistic Missile Division have recently developed, and are now placing in contracts, an exhibit which supplements the standard quality control specification MIL-Q-9858. This standard quality requirement, while suitable for many procurements, was found to be too general in some areas to provide the kind of specific direction to industry which is required on Aerospace Systems.

The supplementary exhibit (DCAS Exhibit 62-10) is being placed on new contracts within SSD. Among other things, it requires that the contractor's engineering and design groups classify inspection characteristics and place the classifications on the drawings. This procedure requires the designer to determine the critical, major and minor characteristics of the design.

The philosophy behind this requirement is that the most knowledgeable individual with respect to a particular design is the designer himself. He, therefore, should be the individual to identify the critical characteristics of critical parts for manufacturing, inspection and handling. This classification of characteristics procedure can result in considerable dollar savings through reduction of scrap, rework, inspection, and manufacturing effort during the manufacturing cycle.

In conclusion, through the collective efforts of the military services and industry, we have made significant strides in fielding reliable systems. The performance requirements and operational environments of tomorrow's systems will require greater strides. We must be continually aware of system reliability requirements and reflect this awareness in every technical, cost, time, or other management decision.

Thank you.

PROCUREMENT PRACTICES FOR RELIABILITY

William W. Thybony, Colonel, U. S. A.
Office of the Assistant Secretary of Defense (I&L)
Washington, D. C.

Introduction

More than ever before the absolute necessity for acquiring highly reliable weapons and equipment is being recognized in both Government and Industry. As to Defense procurement practices having a direct bearing on quality and reliability, there have been several major developments within the past few months.

Notably among these are the positive actions being taken to reduce cost-plus-fixed-fee contracts, to increase the use of incentive type contracts, and to further emphasize value engineering. As a result, our ability to contract for reliable equipment has improved considerably.

These efforts have been motivated and are fully supported by Secretary of Defense McNamara; the Deputy Secretary, Mr. Gilpatric; and Assistant Secretaries of Defense Thomas D. Morris and John H. Rubel, as well as all other top Defense officials involved in this field.

In June of 1961, before the NSIA Joint Industry--Defense Department Symposium on "The Profit Motive and Cost Reduction," Mr. Morris, The Assistant Secretary of Defense (Installations and Logistics) stated:

> "I feel it is mandatory that we increase our use of all our present incentive type contracts. There are very few situations in which there is not an opportunity to employ either performance incentives, value engineering or a combination of these . . . In addition to more emphasis on price analysis, we must sharpen our ability to differentiate between good and bad work. There are several measurable yardsticks which should be readily apparent--meeting schedules, quality and reliability of the product, securing competition in purchasing, emphasis on value engineering, past performance on other contracts."

Since that time the Armed Services Procurement Regulation has been reworked to change the emphasis on the selection and use of the various types of contracts employed by the Department of Defense. By this effort, we hope to improve the quality and reliability of Defense material, as well as reducing overall costs.

Background

The character of defense procurement has been changing, bringing with it corresponding changes in defense industries. While our funds for weapons have continued at a very high level, these funds have not been used generally for high volume production of weapons. An increasing proportion is going into research, development and prototype testing. New weapons and weapons systems are fewer, more complicated and costly with no assurance of large scale production. Follow-on production contracts are not as plentiful as heretofore. These conditions have noticeably affected the nature of our contracting and industrial profit opportunities.

Trends in the usage of the various types of contracts for the last eleven fiscal years show a drastic decline in the percentage of Defense business done under contracts involving substantial pricing risks. Since 1951, the percentage of our procurement dollars in cost-plus-fixed-fee contracts has risen from 13 percent to 39 percent, as fixed-price contracts declined proportionately from 78 percent to 47 percent. This means that we are currently feeding approximately $10 billion a year into the defense industrial community under cost-plus-fixed-fee contractual arrangements that do not discriminate in terms of final profits, between good performance and bad, between early successful accomplishment and protracted failure, between tight management control of costs and waste. Under cost-plus-fixed-fee contracts, the profit is fixed at the outset and does not vary by the quality of performance. In addition, under some of the earlier "incentive" contracts, the profit swing was frequently on too narrow a scale, for instance, from a minimum of 6 percent to a maximum of 8 percent. We believe in such contracts, as in CPFF contracts, we have been providing too little incentive to give any real encouragement for cost control, efficiency, performance and reliability.

Objectives

Our aim is to create and sustain a high level of military procurement efficiency, and cause the same improvements to be brought about in Industry. To achieve this end we plan to reduce to a minimum our use of cost-plus-fixed-fee contracts, and to substitute contracts which provide more motivation for developing or producing weapons of good performance and high

reliability, for early completion and for very close cost control. Obviously, as we move through the cycle of initial development, test, early production, and volume production, the importance of various motivating factors will vary and, accordingly, the contract types will vary.

It is our belief that, for each of the various objectives we seek to accomplish, there must be available a wide range of profits from very low--in some cases, undoubtedly, losses--to quite high, so that the distinction between very good and very bad performance can be rewarded or penalized sufficiently to require the most intensive management attention. By providing this range of possible profits we seek to induce reductions in cost and improved performance that would completely outweigh, as an advantage to the Government, any amounts by which overall profits may be affected.

There is no question in our minds as to the difficulties to be encountered in this multi-measurement approach to incentives. Foremost among these is the task of deriving realistic standards of measurement. Technical requirements will have to be examined in terms of precise specification of reliability levels and agreed formulas developed for measuring and computing achievements.

ASPR Changes

At this time, we are not introducing any new types of contracts. However, pursuant to the foregoing comments, we have made the following specific changes in the Armed Services Procurement Regulation:

1. We are encouraging a much wider use of firm fixed-price contracts. In the past we have tended to use such contracts only when we had extensive competition or we knew from past experience what the costs of performance would be within very narrow limits. In the future we expect to use the firm fixed-price contract whenever we are sure that we can identify the cost risks or contingencies with considerable accuracy and can assure a reasonable sharing of such risks between the Government and the contractor. Contracts of this type, involving as they do the greatest risks and the greatest incentives for cost reduction, can be expected to produce the widest range of profits and losses. This wide spread of profits is the normal result of the extensive use of fixed-price contracts and should not be of concern unless the average profit rate gets too high.

2. We are eliminating virtually all fixed-price redeterminable contract types where the price can be set after all or a portion of performance, and such price covers work already done at the time it was fixed. Such retroactive pricing arrangements encourage high costs up to the point of final pricing since the higher the costs at that point the higher the final price is likely to be.

3. To re-emphasize, we are seeking a drastic reduction in our use of cost-plus-fixed-fee contracts. We hope that we can largely confine the use of this type of contract to research studies and other contractual situations where our objectives cannot be closely defined. Most important, we hope that our large weapons development work, most of which has, in the past, been done under CPFF contracts, can, in the future, be done under some type of incentive contract.

4. As stated, we are seeking a great increase in our use of incentive contracts--a far wider spread, both up and down, in potential profit ranges in such contracts as an inducement to better management efforts, and a very rapid extension of our incentives to matters relating to the quality of weapons, performance and the timeliness of contract completion, as well as to purely cost control matters, with which our past usage of incentives has been principally concerned.

Incentive Contracting

In negotiating incentive contracts it is necessary, in each instance, to determine specifically what phases of contractor performance are important to us. We must then ascribe to such factors sufficient weight, by which we mean a sufficient proportion of the total profit swing, so that those things which are very important receive the greatest inducement for good performance and those which are of lesser importance receive a lesser inducement. The incentive feature should reflect a balancing of the various characteristics which together account for overall performance, so that no one characteristic will be exaggerated to the detriment of the end item as a whole. At the beginning of the cycle of a new major weapon development we would normally be most concerned with assuring that the weapon being developed would perform in the manner we required. If this were a new missile, for instance, we would be most concerned with such factors as range,

payload, accuracy, and reliability. We might ascribe one-half of the profit swing to such factors. Secondarily, because of the necessity for time-phasing this weapon with our own other weapons and with those of potential enemies, we would be concerned with the time of successful completion of development. We might ascribe one-third of the profit swing to this factor. At this stage we might ascribe only one-sixth of the profit swing to the factor of cost control on the theory that extreme attempts at cost savings at the very early stage of the development of a new weapon may deteriorate the quality of the weapon.

Later in the development cycle of the same weapon, say after we had achieved the requisite performance characteristics and were producing for an extensive operational and testing program, we might want to reward performance improvements such as improved reliability, continue to provide some reward for timely performance, but give far heavier weight for close control of costs.

Finally, when all performance goals were assured on a production basis, and we had similar assurance of timeliness of deliveries, we would be concerned only with improvements in cost control. This could be accomplished either by a wide-ranging cost reduction incentive, or by a firm fixed-price contract.

As a highly important feature of this program, we will require, wherever possible in development programs, for more precise determinations on the part of the military departments of desired performance objectives and schedules of completion. As a result, we should be able to make such desired objectives known to prospective contractors in advance of source selection by including them in Requests for Proposals. Then performance and schedule completion targets proposed by each prospective contractor, together with the estimated cost, will be considered in the evaluation and selection of the successful contractor.

We expect many advantages to accrue from this arrangement since it will permit the negotiation of targets and incentive patterns into the contract while competitive proposals are still available. In other words, the individual incentive proposals will be a major factor in the competitive selection of the successful contractor. Thereafter his proposal (as it may be modified in negotiation) will be the basis for the contractual incentive provisions, and will govern the profit ultimately earned.

Thus it will be seen that contractors submitting unduly conversative proposals, or targets which involve little or no risk, will endanger their competitive position and, hence, the likelihood of their getting the award. Conversely, if contractors are unduly optimistic in their promises they will be in danger of being awarded a contract at a very low profit or a loss. As a result, we expect that these arrangements will compel more care and integrity in the preparation and submission of proposals for development contracts. The use of this technique will be extended as rapidly as possible to a large number of weapons development situations. It should substantially increase the objectivity of development contractor selection and should somewhat simplify the procedure of negotiating targets.

In cost-plus-incentive-fee contracts, we have eliminated the administrative ceiling on maximum fee (currently ten percent for research and development contracts), making it possible for full use of the fee range up to the statutory limitation of fifteen percent.

We will strive to make our negotiations of targets and sharing formulas as precise and carefully analytical as is possible. The problem of negotiation of targets is basically no different than the negotiation of the price of any other type of contract, although more difficulties may be anticipated. The hazards, that is to say the pricing risks, to both the Government and the contractor are less in incentive contracts than in firm-fixed-price contracts, but greater than in cost-plus-fixed-fee contracts. These risks provide the motivation for better performance. There is no question, however, that the negotiation of realistic targets, based on full disclosure of accurate and current data, is essential in incentive contracts. We believe more intensive efforts must be undertaken, by both Government and Industry, to develop better estimating techniques and systems for measuring accomplishments. We believe further that increased use of incentive contracts will be an inducement to that end.

Value Engineering

In the near future we will be issuing a policy encouraging the increased use of value engineering techniques and will provide standard contract clauses for this purpose. Through this new emphasis we plan to incorporate incentives for contractors to appraise intensively products purchased by the Government under specifications and to develop and recommend changes in specifications which will enable them to be produced at a measurable savings in cost without adversely affecting the required performance, quality, maintainability, standardization, and interchangeability as determined by the Government. We are speaking of changes in specifications which include, among others, the deletion of requirements found to be in excess of actual

needs as to materials, material processes, tolerances, components, testing requirements and testing procedures. To motivate the contractor to develop and submit cost savings proposals, value engineering incentives will provide for the contractor to share in the estimated contract cost reduction resulting from a specification change proposed by the contractor and accepted by the Government. Through value engineering we expect to wed technical skill to cost sensitivity.

Conclusion

In summary, we have launched a contractual system which rewards risk taking, efficiency and the surpassing of performance and reliability goals. After coordination with many industry associations, we are certain they agree with our incentive contracting philosophy, and that we can depend on their support. Progress will depend on the acceptability of incentive contracts by individual firms. It is imperative that adequate understanding be developed, and that the details of the program and its objectives be adequately communicated to the individuals who will be directly involved, both in and outside of Government.

We believe the tools for doing a better job are now at hand. It behooves all of us to use them.

RELIABILITY SPECIFICATIONS AND THEIR EFFECTS

A. H. Drayner

Martin Company General Offices
Friendship International Airport, Maryland

Summary. This paper covers in brief form the currently significant reliability specifications, and includes a reliability specification "tree" for ready reference. Management requirements for effectively complying with these documents are discussed, and one multi-Division systems manufacturer's organization for reliability management is briefly described. Cost implications of reliability specifications, as well as reliability considerations of incentive-fee contracts are mentioned and several of the current reliability management problems in these areas are reviewed.

Introduction

For purposes of discussion, a specification is conveniently defined as: "A formalized system of documentation, usually relating to details of work to be performed under a contract." In the United States, military specifications have apparently been around for a long time; for example, in a recent paper[1], there was included a reproduction of a cannon ball specification issued one hundred and sixty-three years ago (incidentally, people were not as technically ignorant then as one might think: in this particular specification, there are numerical test requirements for material elastic limit, tensile strength, elongation after rupture, and test specimen area reduction). It is not recorded whether the cannon ball specification was ever cancelled. Since that time military specifications have proliferated in great number, their rate of preparation being greatest since the second World War.

Reliability inclusion in specifications dates from the early 1950's and again, the growth in numbers has been great. Data in this area may be found in a remarkably complete history of reliability that is contained in a recent paper by C. M. Ryerson, covering many of the early documents in the field[2].

Gamut of Specifications

It has been said that there are currently approximately twenty-eight hundred cubic feet of Government specifications extant (accumulation, one copy each). Naturally, these cover a range of topics from "A-Napthol" (a chemical reagent) to "X-Ray Laboratories" (procedures for certification of), across all Government activities.

Specifications appear under many names and forms. In addition to pure specifications, there are also standards, specification bulletins, exhibits, technical reports, notebooks, handbooks, guides, even contract appendices, all of which fall under the above definition.

Additionally, there are a body of intimately related regulatory and directive documents. Publications such as Air Force Regulations, Special Aeronautical Requirements, and the Armed Services Procurement Regulations are very important in our business, but relatively unknown to many reliability organizations.

To reduce quantity and increase acceptability of documentation, elements of industry are continually working closely with the Services in specification development and review. Every trade association with technical activities, and most technical societies, have significant specification committees in fields related to their interests. Many of the aerospace companies also directly contribute the time of specialists to Government agencies on particular tasks.

There are, as well, moves within the Government to reduce the quantity and increase the quality of specifications in specific areas. As an example, the 280 or so specifications and standards for preparation of technical manuals are being reduced to approximately 40 in a determined effort by the Defense Supply Management Agency, Standardization Division.

Reliability Specifications

Here, too, we have an embarrassment of riches. There are in excess of two hundred identifiable Government specifications and documents related to the establishment and support of reliability requirements.

In the type of business in which the Martin Company is engaged we are concerned, essentially daily, with about one hundred of these specifications. They are noted and categorized in figure 1.

In addition, in common with other Aerospace companies, we deal with a number of special "interpretive" reliability specifications aimed directly at such programs as GEMINI, TITAN, PERSHING, BULLPUP, etc.

It is interesting in the examination of a chart such as this, to note the "inversion" phenomenon --- such tremendous general specifications as MIL-W-9411, MIL-E-8189, MIL-E-5400, and MIL-E-16400 become "support" documents when a reliability specifications analyst views the situation!

Because of the wide-spread use of the cited documents in our diversified activities, our Contract Technical Requirements sections prepare abstracts of the most significant specifications, from which concerned personnel can quickly extract pertinent information. The data so abstracted is not meant to be particularly interpretive, but readily provides program planning data for people concerned with the broad aspects of projects.

Major Reliability Specifications

First, and most important to most of us, is the systems type reliability specification. Perhaps the best current example of this is MIL-R-27542, which replaced three other large specifications; MIL-R-26674, MIL-R-25717, and AFBM Exhibit 58-10. These major documents are truly omnibus specifications, almost suitable for text book use. They cover in reasonable depth the thirty or more elements of a complete reliability program, including reporting systems and methods of analysis. (In the case of MIL-R-27542, the sequence of its sections is not one that a program plan should necessarily follow, but most of the information is there).

MIL-R-27542 (USAF) establishes requirements for an organized reliability program to assure attainment of contractual requirements at a specified time for a complete system and its sub-systems, including requirements for collection and reporting of considerable reliability data. General requirements on the systems contractor are:

1. Development of a complete reliability program based on eight fundamental principles;
2. Continuous program review at preplanned steps;
3. Continuous reliability training for all personnel who contribute to product reliability;
4. Responsibility for subcontractors' and suppliers' reliability programs;
5. Inclusion of reliability principles in design, with seventeen examples included;
6. Establishment of specifications and standards for use in manufacturing and inspection, including classification of characteristics;
7. Conducting of design reviews, with approval of reliability organization required prior to design finalization;
8. Conducting of development testing for estimation of reliability in accordance with MIL-R-26667;
9. Demonstration of achieved reliability in accordance with customer approved plans;
10. Collection, summarization, and submittal of many types of data throughout the program.

The complete framework for satisfying the requirements of MIL-27542 must be included in the proposal prior to award of contract, including specific tasks and procedures for implementation and control, and predictions of reliability based on estimated environmental and stress conditions.

MIL-STD-441 (DOD) is specifically concerned with electronics equipment, and is unique in being a Department of Defense document rather than a single service output. It is mandatory for use by the military Departments. It emphasizes:

1. Analysis of feasibility during "Phase I", with extensive utilization of parts failure rate data. It assumes an exponential distribution of failures and requires investigations and allocations to the parts level.
2. Prototype construction and extensive test evaluations during a "Phase II". A major report is required at the end of this phase that provides detailed information covering eleven general consideration areas.
3. Selection and application of standard circuits and parts. It controls utilization of non-standard items through strong approval requirements.

Equipment and Sub-system Reliability Specifications

The next level of documents in this rather arbitrary breakdown covers reliability in design, development, and production of equipments and sub-systems. These seven important specifications are particularized from the equipment class point of view, and in addition, some are phase-related to development or production.

MIL-R-27070(USAF) provides general reliability procedures and criteria for initial development of ground electronic equipment, and details minimum reliability requirements to be demonstrated if this is not covered in the detail equipment specification or contract. It requires tests to demonstrate

achievement of specified reliability at a confidence level of 90% as well as continuous analytical estimates. Since both MIL-R-26484 (USAF) and MIL-R-27173 (USAF) cover much of the same material, this particular document appears to be redundant.

MIL-R-27173 (USAF) is applicable to research and development contracts and details the minimum requirements to assure design and manufacture of reliable ground electronic checkout equipment. If not called out otherwise, it requires a mean-time-between-failure (MTBF) of 300 hours for checkout equipment or 500 hours for major sub-systems and assemblies. Demonstration of compliance is required by tests on at least two items, and test time must be at least three times the specified MTBF. Extensive documentation and approval procedures are established.

MIL-R-26484 (USAF) covers minimum requirements and procedures for reliability that must be followed during research and development of electronic sub-systems or individual equipments. This specification is based largely on MIL-STD-441, and requires at least three times the specified MTBF in demonstration testing, utilizing a cycle that includes five types of multiple environments. Also, unless otherwise specified, it requires a 3000 hour minimum operating life with reasonable servicing, and a test on at least two equipments for the specified longevity time using the MTBF test and cycling. Extensive documentation and approval requirements are established.

MIL-R-26474 (USAF) is based on MIL-STD-441 and is aimed at production ground electronic equipment. It requres a detailed reliability program consistent with this specification and MIL-STD-441. It requires preproduction and production reliability tests on randomly selected samples of equipment that have passed all acceptance tests. Iterative reliability analyses and estimates throughout the program are required in addition to other reliability documentation. The test requirements of this specification are in conflict with MIL-R-26667 (USAF) "Demonstration Requirements" and negotiators should examine this carefully.

MIL-R-19610 (WEPS) outlines minimum requirements for production electronic equipment. It establishes several levels of reliability based on hours of operation and failure criteria. It requires a plan for maintaining equipment quality, and the contractor must establish costs involved, above "normal" quality control costs, to comply with this specification prior to award of contract. A group of tests are specified in lieu of acceptance tests required in the detail equipment specification, plus life tests on equipment selected by the Government Inspector, based on MIL-T-18303 as a guide. There have been numerous detailed objections to this document and its use should be carefully evaluated.

MIL-R-22256 (WEPS) outlines procedures to ensure high inherent reliability in the design and development of electronic equipment or systems planned for production. It requires a thorough reliability program (15 areas of activity are discussed) extending through to completion of model evaluation. Demonstrations for reliability or longevity are not required but several environmental tests are specified. Phase I reports in accordance with MIL-STD-441 are required, as well as preliminary and final Phase II reports. Reports on study, design planning, reliability calculations, tests of detail parts, subassemblies, and circuits are required.

MIL-R-22732 (SHIPS) prescribes procedures for establishing and verifying reliability requirements for preproduction and production ground and shipboard electronic equipment. It requires a reliability assurance plan, calculation of MTBF per NAVSHIPS-93820, and reliability analyses with proposals for redesign as necessary. Tests of several classes are covered, plus production reliability inspections and failure reporting systems. Content, timing and format of numerous reports require definitization.

Auxiliary Reliability Specifications

Next in order of significance, and probably the documents that create more argument than any others, are the "How To Do It" back-ups for the major reliability specifications. Such publications as MIL-R-26667 (USAF) and MIL-STD-756 (WEPS) are included in this group which covers monitoring methods, organization, demonstration requirements, definitions and prediction-assurance-measurement techniques in considerable detail. Several of these documents were originally resisted vigorously by some aerospace contractors because of their definity and their requirement for particular types of organizations and methods. As educational and guidance material they provide a splendid source of information, even when not contractually required.

The three "levels" of reliability specifications discussed briefly above represent seventeen active documents, plus the Naval Weapon Systems document which had not been coordinated at time of this writing. It is instructive to note that most of these specifications are aimed at electronic systems. With few exceptions, all of the techniques employed in current reliability technology were developed around electronic systems requirements.

In addition to the pure reliability documents there are dozens of other specifications, each important in its own right. These "support" documents (Figure 1) are often key specifications in other fields, but are related to reliability efforts in many ways. For example, it is not possible to develop and deliver reliable equipment without taking into full account such auxiliary disciplines as maintainability, human factors, training, quality control practices, and proven packaging techniques. Also, some of the system specifications themselves contain reliability sections.

Reference Documents

Among the most interesting of what we have chosen to call the "support" documents are the "reference" publications, some of which are even good reading! They cover a melange of things, and are in some cases mutually contradictory. It is informative to note that several are actually re-writes of each other, to suit the purposes of individual services. Also, the term "reference document" may be misleading, since some of these are often called out in contracts. In many ways, these publications provide both a history of reliability engineering and an indication of its current status. Three having the most general significance are discussed in succeeding paragraphs.

Giant among these publications is the report of the Advisory Group on Reliability of Electronic Equipment (AGREE). This document was issued in June of 1957, and is often considered to be the fountain head of our modern reliability specifications. The nine task groups of AGREE expanded on the work of the older Research and Development Board's "Ad Hoc Group on Reliability of Electronic Equipment" and really formalized and correlated the manifold disciplines of reliability engineering for the first time. Implementation of the AGREE test procedures has had excellent results in the development and production of reliable electronic equipment.

Another publication of fundamental significance is the report of the Ad Hoc study group on Parts Specifications Management for Reliability (PSMR-1). This is a two-volume document issued in July of 1960 (since the 40 man group was headed by Paul Darnell of the Bell Telephone Laboratories it is often referred to as "The Darnell Report"). The task was an outgrowth of recommendations from AGREE Task Group V. The report confines itself to electronic parts and recommends basic changes in Government organization in the parts specifications area plus fundamental changes in methods of preparing parts specifications to include reliability requirements and demonstration methods.

The sweeping recommendations of PSMR-1 will take considerable time for full implementation. Significant initial reactions are:

1. Changes are being made in Chapter V of Standardization Manual M-200 (a guide on how to write specifications). These are being promulgated rapidly to provide a body of instructions on how to write reliability specifications for parts in general accordance with PSMR-1.
2. The Quality Control and Reliability Division of the Office of the Assistant Secretary of Defense (Installations and Logistics) has prepared and is currently coordinating a manual to supplement Chapter V of M-200. It is called "Manual of Instructions for Incorporating Multi-level Reliability Requirements into Parts Specifications".
3. The Armed Services Electro Standards Agency (ASESA) has been moved organizationally and physically to report to the Defense Supply Agency in Dayton, Ohio.
4. The Space Parts Working Group, under Air Force guidance, is doing an excellent job in coordination of contractor approaches to reliable parts specifications and procurement.
5. Many aerospace companies and their vendors are currently preparing specifications and procuring and producing hardware to the PSMR-1 conditions. It is already apparent that the military-industry teamwork exhibited by this particular adventure is showing big bonuses for reliability and for the nation.

The Interservice Data Exchange Program documents, IDEP-1 and IDEP-2, are currently highly important to all of us. This system is a growing monster, but a benevolent and useful one. Eminently practical, IDEP's key job of exchanging relevent parts test information between contractors engaged in ballistic missile programs is based on two elements: a simple yet complete summary format and a rapid-response handling and distribution system. Current efforts to firmly tie this program into all contracts must be very carefully examined. As a matter of firm policy we participate actively in IDEP across the Martin Company. Naturally, we would not object vigorously to contractual coverage for this program but we would like to be assured such coverage will not complicate the system and slow its response by treatment in common with other contractual data requirements --- DD-250 forms and Government representative review functions, for example, might seriously reduce the current efficiency of IDEP.

A Few Words on Contracts

On 15 March of this year, the eighth revision to the Armed Services Procurement Regulations (ASPR) was issued affecting the contracts section. It is clear from this revision that there is a definite move towards cost-plus-incentive-fee and fixed-price-incentive-fee contracts in our business.

It is also clear that reliability engineers must examine this situation in detail. A significant portion of the postulated incentive fees (which can be either positive or negative) will be based on the demonstrated reliability of delivered hardware.

The following are significant quotes from ASPR, Revision 8:

1. "The objective (of incentive contracts) should be to insure that outstandingly effective and economical performance is met by high profits, mediocre performance by mediocre profits, and poor performance by low profits or losses".
2. "--- the contract type selected should provide for a profit factor that will tie profits to the contractor's efficiency in controlling costs and meeting desired standards of performance, reliability, quality, and delivery."
3. "The introduction of incentives into development is of such compelling importance that, to the extent practical, firms not willing to negotiate appropriate incentive provisions may be excluded from consideration for the award of development contracts."
4. (Under cost-plus-incentive-fee contract description) "The provision for increase or decrease in the fee is designed to provide incentive for maximum effort on the part of the contractor to <u>manage</u> the contract <u>effectively</u>" (underlining is the author's).

Reliability engineers will be compelled to work directly with contracts, legal, and financial personnel. Therefore, it behooves reliability personnel to learn the language and special problems of the people with whom they must deal. There is no longer a place, if there ever was, for the reliability man who is continually unhappy because other elements of an organization do not understand him and refuse to learn <u>his</u> language; now, reliability people must learn the language of management and join the team.

With sub-systems or components, when design and utilization is relatively simple, it is sometimes economically feasible to develop reliability demonstration programs that will provide statistically and legally valid proof of goal achievement within a narrow confidence band. However, when it becomes necessary to combine probability information from sub-system tests to provide, for example, reliability "numbers" for a large weapon system, the techniques for arriving at confidence intervals are so controversial that non-technical people could become very confused.

It seems, then, that the necessary approach for large missile systems will be one of developing contractually acceptable demonstration plans based on "yes or no" situations to complement, not replace, the engineering statistics approach. Such situations might be --- a date met or not, a review held or not, a test passed or not, a countdown sequence completed with no more than a "par value" number of holds, successful mission completion --- in short, the kinds of data that will hold up (if needs be) in a court of law. Probabilistic numbers or gambling odds do not seem to fit here; too many people have heard of the book by Darrel Huff and Irving Deis titled "How to Lie with Statistics"! Accomplishment of the intended mission is the real concern of the customer, and decisions on degree of accomplishment will not be limited to engineering reviews alone when incentive fees are involved.

Management Considerations

Fundamental to the establishment of any channelized type of activity is detailed organization, not only of people and facilities, but also of concepts. The climate induced by reliability specifications constantly reinforces this statement.

In a broad field such as reliability engineering, it is essential that strong interest and leadership be evidenced by top management in an organization. The necessity for this becomes clear when it is realized that, while reliability is fundamentally an engineering discipline, its span of influence cuts across all departmental functions.

In multi-division multi-customer companies it is basic that operating methods be mutually compatible to facilitate inter-division assistance on major programs. Reliability policies and practices must be in reasonable accord, and this generates a requirement for corporate staff direction in this area.

Within the boundary conditions of customer requirements and company policies and procedures, an individual project must be allowed to organize its reliability effort for greatest effectiveness on its particular product. The working relationships of the project reliability organization relative to engineering, manufacturing, quality control,

material, and logistics support functions must be clearly defined by management directives, and monitored by a central reliability operation for effectiveness.

While this is admittedly a very much simplified treatment of a complex subject, the following points are salient:

1. Leadership and guidance, in written directive form, must be provided at company executive level, and repeated in particularized form by successive echelons of management.
2. Directive documents must cover not only the obvious engineering responsibilities for reliability, but also the concomitant responsibilities of the other industrial functions.
3. Audit and review activities for the measurement of reliability organizational system effectiveness must be continuous.
4. The overall reliability plan must be kept sufficiently flexible to accommodate changes in customer direction or state-of-the-art on short notice.
5. Management direction must be strong enough, and consistent enough, to assure that a mutually conformant reliability posture is assumed by all company elements.

Martin Company Approach

In giving emphasis to the subject of reliability, the Martin Company in common with other aerospace corporations has evolved specific management structures and philosophies. The task facing us is typical among the multi-division multi-customer aerospace corporations. Our solution is somewhat unique in that we have become fairly well projectized within each operating Division, and are utilizing a variation of what the Harvard Business School calls the "bi-lateral line" type of organization, from Company headquarters down. Since some of the projects within each of our Divisions are organized very much as a small company is, our major tasks become (1) maintaining the inherent flexibility and discipline of a small company, while (2) realizing the benefits of the tremendous resources and technical cross fertilization influences that only a large company can provide. We believe this has been effectively accomplished in all areas, including reliability.

Reliability Policy and Direction

Reliability leadership and guidance in Martin begins at the "top" with a headquarters office staff function. Full written authority in the reliability area is granted by the President to the Vice President-Engineering. A portion of the applicable section of this authority reads as follows: "--- the establishment of criteria for and control of reliability, maintainability, and training for use and service of aerospace division (Martin Company) products and the development of procedures and measures of performance concerning these activities --- is hereby vested in the Vice President-Engineering."

The relevant portion of this basic charter is implemented by the Director of Reliability, who serves on the staff of the Vice President-Engineering. He is responsible for generation of reliability policy and direction across the several divisions of the Martin Company, assisted by the company Manager of Reliability Systems.

In addition to the general delegation from the President to the Vice President-Engineering, there is also a specific Policy Directive on product reliability issued by the President. Supporting this is a product reliability program Operating Instruction issued by the Vice President-Engineering which defines the scope of activity of the Director of Reliability and establishes requirements on the operating Divisions. Other headquarters Operating Instruction documents in this area cover such things as the Interdivision Reliability Committee, across the board participation in the Interservice Data Exchange Program, and definitive procedures for establishing and conducting design reviews. Similar sets of operating instructions and policy documents cover the areas of standardization, maintainability, engineering facilities, etc. Utilizing these documents to establish boundary conditions, the operating Divisions, and the programs within the Divisions, establish their operating instructions and organization structure, modified if necessary to fit the special requirements of each customer.

The Director of Reliability guides the preparation of reliability portions of major proposals and the establishment of reliability programs on projects within the Divisions. In maintaining active cognizance of the projects, the Director of Reliability assures that the policies of the Company are implemented, and provides a direct channel of communication to top management.

Figure No. 2 shows an example of the overall reliability organization bridging from headquarters to an active project within the Space Systems Division of the Company (one of our Baltimore-area Divisions). The Director of Engineering of the Division acts for the Vice President/General Manager on all reliability matters. His authority is delegated to the Chief Reliability Engineer who is responsible for establishing and implementing Space Systems Division

reliability policy (within the framework of Martin Company policy), for adequacy of reliability portions of proposals, for adequacy of reliability programs on active projects, for the development of methods and procedures, and for acquiring and training reliability personnel to man the active projects. He also provides cross-feeding of information and techniques between projects and a direct channel of communication to Division management and the company Director of Reliability.

Each active project within the Space Systems Division is headed by a Program Director who reports to the Division Vice President/General Manager. The project is staffed with personnel from functional departments, such as manufacturing, quality, and engineering. The project engineering activity is headed by an Engineering Technical Director, acting for the Division Director of Engineering on the project. In most cases we set up an Assistant Technical Director for reliability to manage the line reliability activities on the program. In special circumstances, such as on an integration program or a systems manager project, a special Reliability Program Office is established, under the direct supervision of the Program Director.

Complementary Activities

There are a number of essential activities that complement those of a pure reliability engineering nature. Paramount among these are engineering standardization, specifications control, field support engineering, and data systems.

Each of the noted functions is headed in Martin by company headquarters Directors who operate in much the same fashion as the Director of Reliability.

When a great deal of detailed work must be accomplished, as in the engineering standardization area where sets of manuals are being developed, special overhead accounts are established to plan and control the manpower support provided by the operating Divisions. (As a matter of interest, we are budgeting more than $560,000 from overhead this year to support our engineering standardization effort).

Overall Company coordination in such areas as the Interservice Data Exchange Program and the Battelle Electronic Component Reliability Center is accomplished by the office of the Director of Reliability. In the IDEP area, not only is the company's overall effort monitored but monthly status reports are handled on punched cards, tabed out and supplied to all of the operating Divisions to provide a month-to-month cumulative summary of parts tests planned, parts tests completed in each Division, and IDEP reports submitted. This provides both management and the IDEP Division Data Coordinators with full and complete information on a monthly basis to forestall duplication and to encourage interchange and combination of test plans between operating Divisions.

Cost Elements

It is implicit in specifying reliability that the customer also support the effort financially. This applies not only to analytical areas but also to adequate test facilities for product development and proofing and in the general support areas that require continued expansion and detailed coordination and development to provide a base for reliability progress. We no longer question whether a customer is really serious when he includes a reliability requirement in a request to bid; we know he is. Especially on the larger programs, manpower support for reliability effort is no longer the problem that it used to be, and percentages are ranging quite high for reliability work relative to overall engineering effort on a typical program today.

Such items as the standards effort mentioned above contribute greatly to reliability. Unfortunately, because of the wide-spread application to many programs, it is virtually impossible to direct-charge this type of effort to projects with any degree of integrity. Some means of handling this needs to be found.

Historically, in many elements of the industry, computer machine centers are part of overhead. Now they must be expanded to provide complete data center controls for reliability purposes, for handling PERT and its variations, for handling CHAMPION, and other similar programs that are relatively new. We understand that some contractors have a serious problem in the area of computer funding in support of such things as PERT; this apparent inequity warrants investigation. The situation is created by having some contracts "in the house" that do not allow this effort, and normal accounting systems cannot resolve the problem if these costs are carried in overhead.

The total reliability process must be understood by all the people that are concerned with it. Specifications establish boundary conditions but they do not create reliability of and by themselves, nor do numerical analyses. Reliability must be engineered into a product, then kept in it through intensive work in the manufacturing and use areas, and proofed so that non-technical people can believe it --- note "believe"; this is an all-important factor too often shrugged-off by the technical sophisticate.

Conclusions

There is a need for continuing joint effort between the Services, the Department of Defense, the National Aeronautics and Space Administration, and Industry to reduce the number of reliability documents extant. There is a strong trend in the direction of systems effectiveness requirements rather than reliability per se which will increase the bulk of documents in this area. There is need for more work on effectiveness measurement of reliability programs as such; things in this area are still far too subjective.

Incentive contracting inevitably gets down to the basic measurements of cost, schedules, and performance (which includes reliability). It requires attention to detail planning and a careful look at the proportion of total program effort devoted to reliability. There is an obvious necessity for increased business maturity in contractor reliability organizations. Many reliability groups have difficulty operating "in-house" with a full awareness of their inter-relationships with other departmental functions and fail to appreciate the effects of unilateral action on other elements of their organization.

Engineers operating in inter-disciplinary areas such as reliability and maintainability are growing closer to contract administration and contract structure due to the application of specifications with "teeth in them", and the current complexion of contracts. This requires cross-education beyond traditional disciplines, and if possible, the reduction of some of the extreme specialization that exists in reliability organizations today.

Methods of funding must be reviewed and revamped in those areas that create "blanket" reliability improvement, such as engineering standards, test facilities, and data centers.

Finally, while reliability analytical techniques have been developed to a high state of maturity, methods for measuring the efficiency of reliability organizations have not. The time is ripe to launch a concerted effort to develop acceptable methods for evaluating organizational performance in the reliability field without the necessity of waiting for final hardware deliveries.

References

1. H. L. Wuerffel, "Military Specifications Affecting Reliability," Proc. 7th National Symposium on Reliability and Quality Control, pp 56-83, Philadelphia, Pa.; Jan. 1961.

2. C. M. Ryerson, "The Reliability and Quality Control Field from Its Inception to the Present," Proc. IRE, vol. 50, pp 1321-1338; May, 1962.

GOVERNMENT DOCUMENTS ESTABLISHING AND SUPPORTING RELIABILITY REQUIREMENTS

PREPARED BY:
CONTRACT TECHNICAL REQUIREMENTS
MARTIN MARIETTA CORPORATION
BALTIMORE 3, MARYLAND
MAY 2, 1962

MAJOR RELIABILITY DOCUMENTS

AEROSPACE SYSTEMS AND SUBSYSTEMS
MIL-R-27542(1)(USAF)

MILITARY ELECTRONIC EQUIPMENT
MIL-STD-441(DOD)

NAVAL WEAPON SYSTEMS
MIL-R-(IN PREP) (WEPS)

RELIABILITY IN DESIGN, DEVELOPMENT AND PRODUCTION OF EQUIPMENTS AND SUBSYSTEM SPECIFICATIONS

PRODUCTION-GROUND ELECTRONIC EQUIPMENT
MIL-R-26474(USAF)

DEVELOPMENT-GROUND ELECTRONIC EQUIPMENT
MIL-R-27070(USAF)

GROUND CHECKOUT EQUIPMENT
MIL-R-27173(USAF)

DEVELOPMENT-SYSTEMS AND SUBSYSTEMS
MIL-R-26484A(USAF)

PRODUCTION ELECTRONIC EQUIPMENT
MIL-R-19610(WEPS)

DESIGN-EQUIPMENT AND SYSTEMS
MIL-R-22256(WEPS)

SHIPBOARD AND GROUND ELECTRONIC EQUIPMENT
MIL-R-22732(1)(SHIPS)

OTHER RELIABILITY DOCUMENTS

DEMONSTRATION REQUIREMENTS
MIL-R-26667A(USAF)

INDEX DETERMINATION FOR AVIONIC EQUIPMENT
MIL-R-22973(WEPS)

ASSURANCE FOR PROD. AVIONICS EQUIPMENT
MIL-R-23094(WEPS)

MONITORING
USAF SPEC. BLTN. 506

ORGANIZATION
USAF SPEC. BLTN. 510

DEFINITIONS
MIL-STD-721(NAVY)

PREDICTION TECHNIQUES
MIL-STD-756(WEPS)

MEASUREMENT
MIL-STD-757(WEPS)
(PROPOSED)

SUPPORT DOCUMENTS

QUALITY CONTROL
MIL-Q-9858(2)(DOD)
NPC 200-2 (NASA)
NPC 200-3 (NASA)
DCAS EX. 62-10 (USAF)
DOD-HDBK-110

INTERFERENCE
MIL-E-6051C(USAF)
MIL-I-6181D(USAF)
MIL-I-16910A(2)(SHIPS)
MIL-I-26600(2)(USAF)
PD-R-186(ABMA)

PRESERVATION AND PACKAGING
MIL-P-116D(1)(DOD)
MIL-P-9024B(USAF)
USAF SPEC. BLTN. 56AF
MCP 71-163

HUMAN FACTORS
MIL-STD-803
MIL-H-22174(BUWEPS)
MIL-H-25946(USAF)
MIL-H-26207(USAF)
BSD 61-99(USAF)

TEST METHODS
MIL-STD-202B
MIL-STD-446
MIL-T-4807A(USAF)
MIL-E-4970A(USAF)
MIL-E-5272C(1)
MIL-T-5422E(1)(ASG)
MIL-T-18303(WEPS)

ENVIRONMENTAL FACTORS
MIL-STD-210A
MIL-T-152B(DOD)
USAF SPEC. BLTN. 106A
USAF SPEC. BLTN. 115(1)
USAF SPEC. BLTN. 523
ANC BLTN. 22

DESIGN
MIL-STD-439A
MIL-E-4158B(2)(USAF)
MIL-E-5400E(ASG)
MIL-E-8189B(1)(ASG)
MIL-W-9411A(2)(USAF)
MIL-E-16400D(1)(SHIPS)
MIL-E-19100A(SHIPS)
MIL-E-19600A(WEPS)
ANA BLTN. 444
AD 114274(ASTIA)
AD 148556(ASTIA)
AD 148907(ASTIA)

PROVISIONING
MIL-B-5005A(2)(DOD)
MIL-E-17362C(1)(SHIPS)
DOD INSTR. 4151.7
MCP-71-650(1)
MCP-71-673(1)
PP-SIG-SE-1A
SAR-398
SAR-400

WIRING
MIL-T-713A(3)(DOD)
MIL-W-5088B(ASG)
MIL-W-8160D(USAF)
PD-E-53 ABMA

ENCLOSURES
MIL-STD-108D(1)
MIL-C-172C-1D(DOD)
MIL-E-2036C(3)(NAVY)

INSTALLATION
MIL-I-8700(ASG)
MIL-E-25366C(USAF)

MAINTAINABILITY
MIL-M-26512B(USAF)

DATA
MIL-D-9310B(2)(USAF)
MIL-D-9412D(2)(USAF)
MIL-D-26239A(USAF)
MIL-D-70327(1)

SAMPLING
MIL-STD-105B
MIL-STD-414
DOD-HDBK-106
DOD-HDBK-108

EQUIPMENT TYPES
MIL-STD-243
MIL-C-3098

VIBRATION
MIL-STD-167

TRAINING
MIL-T-4860C(USAF)
MIL-T-26046(USAF)
MIL-T-26137B(USAF)
MIL-T-27382(USAF)

TEST EQUIPMENT
MIL-STD-415B
MIL-T-945A(2)(DOD)
MIL-T-18306A(WEPS)
MIL-T-21200C(ASG)

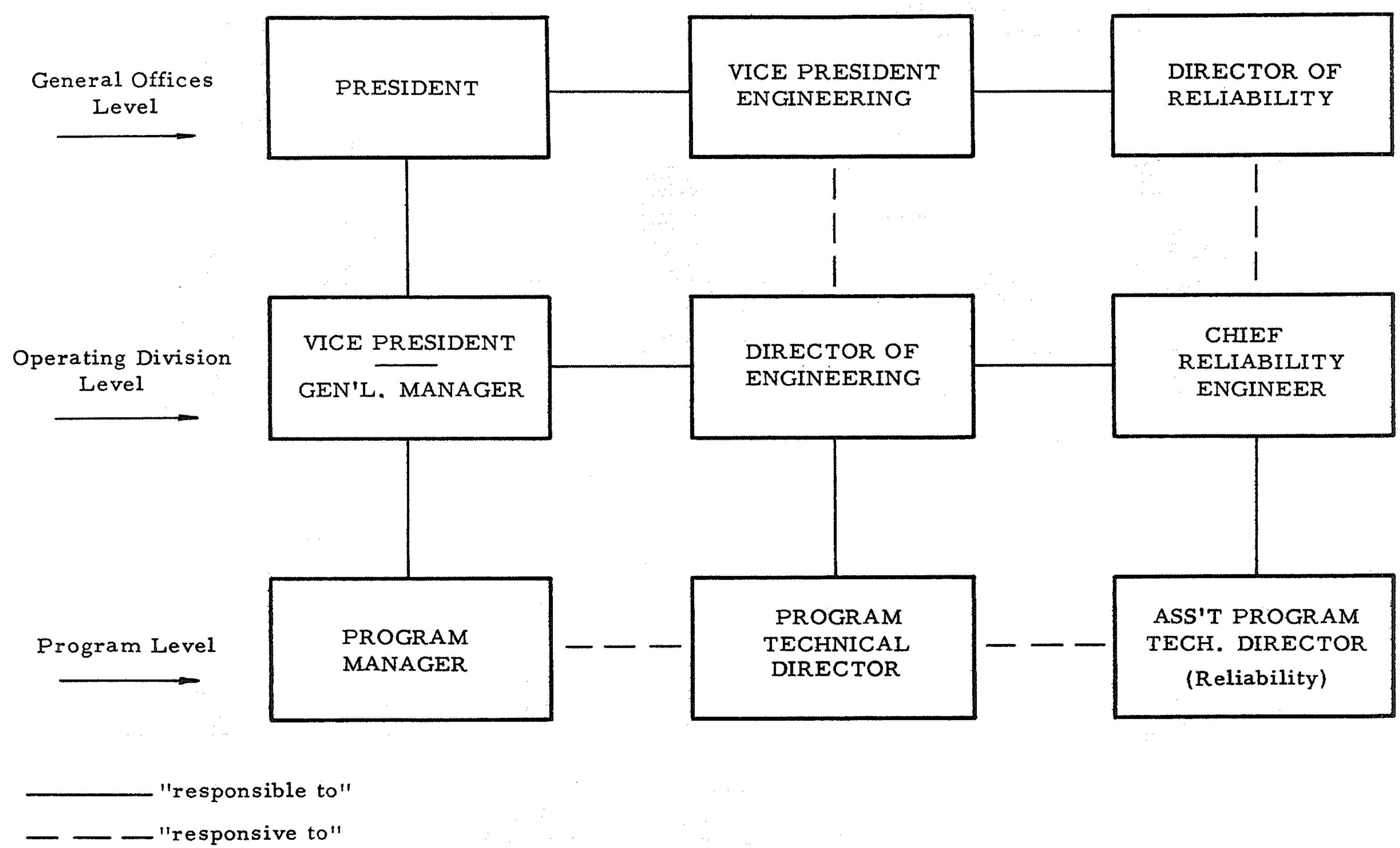
REPORTS
MIL-R-18301(WEPS)
MIL-R-18136A(2)(WEPS)

TEST REPORTS
MIL-T-9107(1)(USAF)

REFERENCE DOCUMENTS
AD148868(ASTIA), RADC Reliability Notebook TR-58-111
PB-121839, Navy Reliability Design Handbook
NAV-AER-16-1-519, Handbook of Preferred Circuits
NAVSHIPS 900-193, Rel. Stress Analysis for Electronic Equipment
NAVSHIPS 93820, Handbook for Prediction Shipboard and Shore Electronic Equipment Reliability
NEL, Suggestions for Designers of Electronic Equipment
AGREE Report, Reliability of Military Electronic Equipment
Reliability Engineering Notes - Diamond Ordnance Fuze Laboratory
Reliability Analysis Data for Systems and Component Design Engineers - Dept. of Comm. PB 181-080
MIL-HDBK-217 (WEPS) Rel. Stress Analysis
PSMR-1 Parts Specification Management for Reliability
1DEP 1 and 1DEP 2

MARTIN

Figure 1



MARTIN COMPANY
FUNCTIONAL RELIABILITY ORGANIZATION

Figure 2

RELIABILITY ANALYSIS AND PREDICTION

G. Ronald Herd
Booz, Allen Applied Research, Inc.
Bethesda, Maryland

Every space program today is confronted with the dismaying problem of equipment failure. Despite all the effort and money devoted to these programs, our results consistently show inadequate reliability. Management has not been sufficiently alert to make use of all the available means for combating these problems.

The emphasis on controlling schedules, while entirely proper in itself, creates pressure throughout the program. Care must be taken to control the response to these pressures--to assure that performance is not always sacrificed to promptness. One means of doing this is by actually integrating reliability analysis and prediction techniques into our programs.

During the past 15 years, the emphasis on reliability for missile and space applications has resulted in the formation of reliability engineering groups in all organizations. During this period, numerous techniques have been developed and used by reliability specialists. The primary aim in developing these techniques has been to answer the question, "What is the reliability of a given system?". Only recently have these techniques been forwarded as tools for designers and management. Some design engineers have learned to use these analytical techniques, but there has been universal failure to recognize the value of these same tools to management. The designer uses reliability analysis techniques to evaluate alternate concepts or designs. Management should use these same techniques to evaluate the trustworthiness of the design concept and the resultant design and to aid in the allocation of cost, engineering effort, and time.

At present, management is so engrossed in the application of PERT in controlling time schedules that performance is being permitted to disappear into a chaotic chasm of inadequacy. Meeting schedules has become so important and understanding of possible time-cost-performance trade-offs is so limited that we will soon be meeting launch schedules but putting only useless piles of junk in orbit overhead.

Aspects of Reliability

There are three important aspects of reliability: achievement, assessment, and maintenance.

Achievement of high reliability depends upon the ability of the technical man to determine the relations among basic physical parameters and the environments, to understand these relations and know how to apply them, and to evaluate the degree of application.

Assessing the degree of achievement of reliability is a measurement problem and can be accomplished in a variety of stages in the development cycle of a system. It is obvious to all of us that during the key development period of a system, classical measurement techniques are not applicable. It is only during the latter stages, when hardware is available for testing that classical measurements can be used. In the critical early period of development, however, reliability analysis and prediction can furnish us with a priori measurements which are extremely valuable when and if we know how to interpret them.

Maintenance of reliability is another type of control problem--one with which we are all familiar. The requirement here is that we eliminate or reduce to a minimum the human errors involved in assembly, diagnosis, and utilization of the system.

Reliability analysis, then, can be described as "a way of assessing the achievement of reliability before testing and use experience are available." Management can use this type of analysis to introduce the performance dimension into the Program Evaluation and Review Techniques (PERT) programs currently in use.

Reliability Analysis

Reliability analysis is the missing link in the control of system reliability. It furnishes a formalized method of evaluating the design

during the research and development phase. Currently it is the only control technique that is sensitive to changes in reliability. It measures one of the performance characteristics--reliability--which is assumed to be integrated into PERT programs but actually is ignored rather than integrated under the pressures of PERT.

How do we now make up the slack in our time schedules? Do we do it by speeding up our development?--No! We do it by lowering our performance requirements or by eliminating critical testing and evaluation phases which assure the performance--reliability--requirements. Management is not evaluating trade-offs--merely trading away performance in favor of time and cost.

All systems are made up from basic components or elements. The procedure of computing loads or stresses and evaluating the effect of these stresses furnishes the framework for an analyst to determine the hazard associated with each element in its expected operating environment. It is the designer's task to insure that the total hazard obtained in assembly of a system be at a minimum. Hazard here is used in the sense of risk and is usually measured by the failure rate. The assignment of quantitative values for failure rates to elements of the system is an important aspect of design analysis and is essential for reliability analysis.

An early step in the reliability analysis is the development of an abstract pattern of analysis or model which is representative of the physical system under consideration. The models are usually mathematical in nature and are used to evaluate the relative worth of alternative designs and to predict the effects of questionable designs. The parameters for the models are determined from past experimental evidence in laboratory testing programs and in field and test experience on previous systems. The basic reason for bringing the mathematician into the picture at all is that the engineers face unknowns at many points. Only through probabilistic treatment can these unknowns be quantitatively considered.

A mathematical model furnishes a consistent set of ground rules and provides a numerical, rather than an intuitive, basis for evaluation and selection of designs for components, assemblies, and systems. Manipulation of such models involves the mathematical techniques of probability theory.

Assignment of quantitative values for the parameters of our reliability model is an important aspect of design analysis and is essential to reliability evaluation. The parameters are usually failure rates, and the values are functions of the design (strength) of the elements, their interconnections, and the environmental conditions. The basic information applicable to many systems is the part failure rate. We must determine the failure rate and the conditions for which the rate is applicable; make the translation to the set of conditions existing in the new system; and take into consideration the interface problems among parts and among circuits in the same power or functional line, realizing that this interface is affected by the failure modes, environment and past operating history.

We have found from bitter experience that every individual must have objectives and milestones to enable him and his superiors to evaluate his progress. It is only through demonstration that he is meeting these milestones that an individual will continue to make effective progress. The design of a system for high reliability is an area where we need to set up objectives and milestones for ourselves. We must be able to evaluate our achievement of these without submitting to the 5- to 10-years' delay required for operation of the current, lengthy feedback loop. So this is one area where we have failed to utilize the tools that we have available.

If we review the industrial growth of our economy with its emphasis on mechanization and automation, the evolution of reliability control programs is readily traceable. As a result of reliability problems, customer service functions were initiated. Then inspection procedures were introduced into manufacturing processes. Later, quality control became an integral part of the manufacturing process. Today, scientific control in the form of reliability analysis is necessary in the design of our complex systems. A reliability program is a method of establishing effective management control over the design of complex systems.

Weak Areas of the Analysis Techniques

Where are the areas of weakness in these analytical techniques? There are two areas of major importance. These are in establishing the basic failure rates from which to build the analysis and in considering the interactions within a functional series of elements.

What is the failure-rate problem? It has its origin in our definition of failure, in stress-exposure variations, in the variation in observation periods, reporting efficiency, and reporting accuracy.

1. Definition of Failure--In an operational system, each item is subject to a different definition of failure. For example, electronic parts employed in circuits with different tolerances require different definitions of failure.

2. Exposure of the item to stresses--Each item employed in a circuit or group of circuits is subjected to different levels of stress, due to its particular position in the circuit and the position of the circuit in the system and black box.

3. The time of observation--All observations on the system are controlled by decisions which are usually independent of the systems under observation. At times we start observing the system after it has been in operation for some time and know nothing about its previous history. On other occasions we are able to observe a system for a fixed period of time during its original employment. In both situations, the only information available is the information that was obtained during our period of observation.

4. The efficiency of reporting--All failures are not reported. This may be due to the pressures imposed upon the staff, or it may be due to the differences in interpretation of the concepts of failure.

5. Missing data--Not all pertinent information is available to the individual completing the malfunction reports at the time of the malfunction. For this reason, and due to human error, some information will not be recorded.

How do we resolve these apparent major obstacles in establishing basic failure rates? We do this by using as our basic inputs, experience on parts or components obtained in tests so designed that the above problems do not materially affect the results. We must know the conditions under which the failure rates are determined; then, using trade-off relations that are almost universally accepted throughout industry, we can translate the basic failure rates to the rates applicable to the particular system under consideration.

The second major problem is the interaction among elements of the system. This interaction problem is not as obvious as the failure rate problem. Drift of electrical characteristics, noise in a servoloop, tolerance changes due to wear, etc., are examples of this problem We know, as we build a complex circuit, that the larger the number of circuit elements, the more difficult it is to understand all of the characteristic variations within the circuit. If we understood all the cross currents, transient effects, etc., and knew how to isolate channels, elements, and functions, then it would be almost as simple to design a 200-element circuit as a 2-element circuit. At present, we do not have this complete knowledge, and our inadequacies are inevitably reflected in the reliability.

Now turning to your own experience, think of any number of problems you have experienced—intermittent malfunctions, the noise in servoloops which has caused wandering, and the errors in digital computer operations. Many of these troubles can't be assigned to any particular part; however, the circuit or system failed. Our experience has been that about one time in three it is impossible to substantiate the existence of a failure in a rejected system; and that nine out of ten part replacements are due to a change in part characteristic rather than to an abrupt catastrophic-type failure.

How do we consider the effect of element interaction or lack of independence in a reliability analysis? There are no well established and rigorous techniques. This part of the analysis is more of an art than any of the other phases. To date we have established, on the basis of empirical evidence, that the average failure rate per part increases with the length of the functional string. This same empirical evidence has indicated that digital circuits and analog circuits have different amounts of interactions. This experience is compatible with our intuitive expectations and our general knowledge of circuits. Therefore, the technique that is currently being used is to determine those elements within a functional string which will interact with each other and use this as the basic interaction building block in the reliability analysis. Within the interaction building block, the estimate of the effect of interaction is based upon the "active element group" as first proposed by Task Group I in

the AGREE report. Deciding how large the interaction building block should be is in the realm of art at present. However, this technique has been repeatedly put to test, and to date I know of no better way of assessing the effects of dependence among electronic circuit parts or among moving mechanical parts.

I recognize that, for accurate reliability measurement and precise definition of reliability problems there is no real substitute for operational time on a given system. However, the reliability analysis permits some degree of measurement and problem definition in the design phase, before testing can be accomplished. Information derived from the analysis compensates for its lack of precision by its timeliness and the resultant savings obtained by eliminating problems before they are built into the hardware. Our experience has been that problems can be identified and the relative magnitude of the problems can be assessed quite accurately. We have not been equally successful in establishing the accuracy of our time scale. The accuracy of the time scale will vary from system to system; but for large complex systems, the scaling on the time axis should not be in error by more than a factor of two.

Industry and Management Employment

Industry and management have a number of problems in the utilization of reliability analysis. From our experience, I would conclude that the key problems are the following:

1. Failure rates are not realistic.

2. Derating is not accurate, particularly in load-sharing redundant applications.

3. Interactions are not considered.

4. The reliability of sensing and switching devices in stand-by redundant applications is ignored.

5. The effects of transients are ignored. In one case at least, a failure pattern reflected the dampening effect of transients through the circuits.

One other major problem is the tendency of people associated with a program to rationalize rather than face up to unfavorable results obtained from an analysis or testing program. Such unwillingness to acknowledge unpleasant facts has disastrous effects on reliability, schedules, and costs.

We have the analytic tools to analyze the reliability of a design; we have demonstrated their application; we know their weaknesses--now it is time for all levels of management to apply reliability analysis and prediction to the difficult job confronting them--controlling the design of a complex system. My plea is that we incorporate system reliability analysis into our PERT programs and begin to control performance rather than allow the deterioration of performance to resolve all of the scheduling obstacles identified by PERT.

DESIGN RELIABILITY MEASUREMENT AND EVALUATION

W. T. Sumerlin
McDonnell Aircraft Corporation 360530
St. Louis, Missouri

17267

Summary

Reliability measurement by data collection and evaluation is considered. Parameters are defined and restrictions established. Reliability estimation of sub-systems and parts as a preliminary to system estimation is reviewed, and rules are established. Confidence levels of sub-systems and parts versus combined system are analyzed. Estimation planning is discussed. Tests planned for accept-reject reliability decision are very briefly considered.

Introduction

Measurement of the reliability of a favored product about to be released, or the confirmation of low reliability in a suspect new model has seemed to many of us for a long time to be an elusive technique. Not so for the item of long acclaim or for the item regularly requiring chronic maintenance. In the latter case, records provide inescapable or irrefutable data from which we all can make calculations that few will question. In the former case, we must create data not already available, run tests, experiments that perhaps are costly of time and money, and then we must be prepared to stand accused of designing the test or experiment to insure the kind of data that gives the desired result. In looking back to the fall of 1955 and the handful of men who gathered with the author to "develop.. tests..which will prove conclusively that the equipment will meet the minimum..reliability established",[1] and were identified as AGREE Task Group 3, it would seem that guidance was provided by Providence. For not until January of 1962, was proof established[2] that certain statistical liberties, taken by Task Group 3 in ignorance, or rather perhaps because of engineering intuition, were more than justified in the interest of testing economy. In spite of this staunch 1957 AGREE milestone for quantitative reliability acceptance decisions, we still need to clear away the haze that surrounds a suitable technique for estimating or measuring the quantitative reliability that is inherently contained in a product not yet mature enough to have acquired a performance reputation. It is the intention of this paper to apply an engineer's consideration to this clarification and to expose the statistical quirks to the light of day in such a way that no one needs suggest that "the numbers game" can prove anything.

Reliability measurement occupies special attention in the engineering profession because it outwardly requires probability theory to estimate the frequency of performance failures that haven't taken place yet. Further, because we don't always determine the cause of all past or future failures, we need statistics to substitute for the pertinent laws of physics which we haven't yet assigned. The first part of this paper will be confined to means for estimating the best quantitative figure for reliability from data obtained by tests of a sample. Sampling is required in the time domain where we examine behavior or performance for a restricted period of time or number of cycles and from this attempt to describe behavior or performance for the extended future. Sampling may also be required in the population domain, where we observe some but not all the items which are of interest to us, and from such observations, we make statements about other similar items which we did not observe. Not infrequently, we will be working with both kinds of sampling simultaneously.

Reliability Assessment

If by the term reliability assessment we mean the assignment of quantitative reliability numbers to an item or product of interest, then it must be noted that reliability prediction is concerned with the reliability assessment of a design without the benefit of hardware observation. Reliability measurement, on the other hand, is concerned with the assignment of quantitative reliability numbers by virtue of insight from observation data acquired from representative hardware under representative conditions. In actual practice, there will be many occasions where it is expedient to develop quantitative assessment numbers for a complex system by a combination of both techniques.

Measurement Parameters

It is regularly found that inconsistency in applying certain restrictions to the important reliability measurement parameters results in significant descrepancies in the results obtained. Accordingly, the important parameters must be identified, and then these restrictions discussed.

Time Domain Parameters. Number of failures (f) and applicable time interval (t) permit calculation of mean time between failures (MTBF), or its reciprocal, failure rate (λ). Either, when inserted in an appropriate distribution function, permits calculation of the probability of occurrence (P) of any specified number of failures, as well as the confidence (C) with which certain statements can be made concerning the measured item or its counterparts.

Population or Cyclic Domain Parameters. For the assessment of the reliability of certain kinds of items where time duration of operation is not significant compared to the cycles of operation, such as in actuators, switches, fuses, and one shot devices, we need failures (f), and cycles, and units(n) from which to calculate unit reliability (r). The latter, when inserted in an appropriate distribution function, permits calculation of the probability of occurrence (P) of any specified number of failures in a given population, as well as the confidence (C) with which certain statements can be made concerning the measured items or their counterparts.

Failures. In basic reliability theory, this author always identifies three kinds of failures, namely, initial, wearout, and random. Initial failures are those which result when an item is not right to begin with, regardless of whether the failure to perform was present from the start or appeared during the early failure period. Wearout failures are those whose time of occurrence can be successfully predicted because of a constant mean time of occurrence and a small variance about this mean. Thus, wearout failures can be prevented by preventive maintenance which replaces a failing item economically just before failure takes place. Random failures are the failures that support most or all of our reliability activity, and need be defined simply as failures whose time of occurrence is random to the extent that it cannot be predicted sufficiently to permit elimination by preventive maintenance techniques. Thus, random failures include those wearout failures which occur so infrequently as to prevent recognition, and they include those initial failures which cannot conveniently be screened out by an economical burn-in or check-out period. In general, if the failures in the random category make up a sufficiently heterogeneous collection, randomness is guaranteed, and this is most always the case.

In collecting failures by test from which to make measurement calculations, there are many temptations to omit certain failures from the count. No performance failures of the item in test occasioned by a fault within the tested item (and this must be presumed unless an external fault is actually found) can be neglected unless it can be shown beyond question to be an initial failure or a wearout failure. If an initial failure, all test time acquired up to the moment of such failure must be neglected if the failure is ignored. If a wearout failure, an acceptable preventive maintenance procedure must be applied, and then the failure may be ignored only if all subsequent similar failures are, in fact, prevented by virtue of the preventive maintenance routine. The fact that a design change is made immediately following a failure which will successfully prevent any recurrence of similar failures is not sufficient reason to discount the failure while counting the accumulated time. The tested item may have thousands of different design shortcomings each of which will produce a future failure. Thus the reduction by one of the different ways a failure may take place gives no license to suggest the future failure frequency will be measurably decreased. Also, since repetition of a sampling test on the same kind of item violates a basic law of statistics (which says that any desired outcome may be observed if sufficient repetitions of the test are made), test time and related failures cannot both be ignored with immunity for any reason save a proven initial failure. A new test or retest must be preceded by significant design change or improvement.

While a single failure may result in immediate damage to several related parts of the tested unit, and the replacement of these several parts need be counted only as a single failure, there will be other cases where more than one part will appear to have failed simultaneously with no reasonable explanation as to a relationship between or among the failed parts. If tested unit performance is prevented by several unrelated parts failures all of which seemed to occur simultaneously, each unrelated part must be counted as a separate failure and the simultaneous time of occurrence classified as coincident. Conversely, there need be no limit to the analytical effort applied to prove relationship between several simultaneous parts failures.

Applicable Time. Hardware has frequently been shown to simultaneously possess more than a single characteristic mean time between failures (MTBF). For instance, many equipments do not have infinite storage or shelf life, and thus have a significant though high MTBF applicable to storage or shelf conditions, and it may well vary with different such conditions. Observation of hardware under such conditions to permit measurement of storage MTBF is often complicated because we cannot establish failure (and thus, time of failure) without putting the item in operating condition, and this change of state for the item may well contaminate the observation. The point to be made is to emphasize an adequate description of the conditions under which a measure of the reliability is desired, and then collect observation time only for the time of exposure to the applicable conditions. If certain time intervals are to be ignored because they are necessary to establish proper initial operation, or for other justifiable reasons, make sure they are thoroughly defined beforehand, so that no option depending on failure observations is present.

In planning the duration of a proposed test, it is well to be prepared to continue the test long enough so that with barely sub-marginal reliability there will still be enough failures

observed to provide a starting point for consideration of design improvement. This factor was the basis for requiring observation for a minimum time period computed as three times the desired MTBF for pilot production equipment, AGREE Task 3, and thus a minimum of 12 failures, on the average, from which to start design improvement on rejected equipment.

Units and Cycles. If MTBF is constant in a given situation thus establishing the appropriateness of the Poisson distribution for measurement calculations, and such assumption is reasonable in a majority of situation, (and correspondingly all units which are to be observed under test are beyond their early failure period), then it makes no difference whether we accumulate unit hours of operating time and related failures from one unit over a long period or from many units over a short period. However, there is an important consideration. If our total future concern is confined to a single unit and that is the unit we will test, then our probability conclusions will involve sampling only in the time domain, and the confidence we acquire by test duration need only be sufficient for the period of our concern for future use (perhaps a "mission" time). If on the other hand, we expect to draw conclusions from the test of a few units which we will apply to a large population of units, then our observation must be extended sufficiently to give us desired confidence both as to future time period (mission) and as to population. As an example, suppose from test data we conclude a missile has a 0.90 reliability with 0.90 confidence. We have then stated that nine times out of ten the missile will demonstrate 0.90 reliability. In launching a hundred missiles as many as ten might be presumed to be unsuccessful, and this would prevail nine times out of ten. Thus if on nine of ten occasions to launch a hundred missiles there were never more than ten that failed, on one of the ten launchings (of the hundred missile salvo) the reliability might be less. From the same test data we could also calculate a new and lower value for reliability but with a higher (than 0.90) confidence. Accordingly, we are able to describe with specific limits all future trials, but we find that our need to spread our expectations over many different units in a large population encourages us to extend our test observation to yield higher confidence. It would seem obvious then to attempt to increase the number of units in our test sample rather than to extend the confidence solely by a longer test, for this gives us protection against unit variation.

There are many cases where it will be found that the literature urges that tests be run on no fewer than two units for reliability measurement. If test conclusions are to be applied to a large population of assumed identical units, a test observation of no less than two guarantees that test findings will not be based on a single unit which is radically different from the rest of the lot.

Probability and Confidence

Distribution functions such as the Poisson and the binomial permit us to calculate the probability of observing any predetermined number of failures with a given reliability (MTBF or λ for the Poisson, and number of units in test sample plus MTBF or λ for binomial). Thus we are also able to compute the probability of observing more failures than a given number, given a particular reliability. This in effect says that if the reliability, r, were so bad that there was P probability of observing more than f failures, then we have P = C confidence that the reliability is at least r, based on observing f failures.

As an example, suppose 1000 unit-hours of test produced but one failure, and a statement of MTBF with confidence was desired. Scrutiny of Molina's Table II[3] shows that for a = 3.9 (and a = t / MTBF where t is the 1000 unit-hours of test), and c = 2 (where c is interpreted to mean two or more failures), then P = 0.9008. Hence, if a figure for MTBF is chosen such that t/MTBF equals 3.9 then there is a probability of 0.9008 of observing more than one failure. And thus for an MTBF = 1000 / 3.9 = 256 hours, we have a 90% confidence.

As a second example, in one hundred trials of a unit there were ten failures. From the Cumulative Binomial Probability Distribution[4] we find that if the probability of failure for a single unit, p, were as high as 0.15 (and hence its reliability equal to 1 - 0.15 = 0.85) then with 100 units in the sample (n = 100) and r = 11 (this table uses r equivalently to Molina's use of c, in this case meaning eleven or more failures), P = 0.90055. Hence if reliability were as low as 0.85 there would be 90% probability of more than 10 failures in 100 trials and we have 90% confidence that reliability is 0.85 or more from observing 10 failures in 100 trials.

Assessment of Systems, Sub-systems, and Parts

Measuring the reliability of systems is often considered easier than measuring the reliability of the sub-systems or parts that make it up, because with the entire system under test, failures occur more frequently, and a shorter test builds up a higher level of confidence in the needed reliability. (Such system testing also eliminates need for considering application factors for piece part test data.) For example, if we remember that a test which observes one failure permits us to have 90% confidence that the MTBF is at least 1/4 the value obtained by dividing the unit-hours of test by the one failure, then a 1000-unit-hour system test would permit us to say we had 90% confidence that the MTBF were at least 250 hours (accurately 256 hours, see earlier example). If the system were in fact made up of ten identical sub-systems, we could expect it to take ten times as long to produce one failure on a sub-system, or 10,000 unit-hours to run a test that would give us 90% confidence that the sub-system MTBF were at least 2,500 hours. And, anomalously, with such

a 90% confident conclusion we should have to acknowledge that on the average one of every ten such sub-systems might be lower than 2,500 hours MTBF, and if this happened in the group of ten sub-systems making up the given system, then the latter could not be expected to have 250 hours MTBF or more. If we had been unsure that all ten sub-systems were identical and had instead tested each of the ten for the 1000 hours which we would have given the system as a whole, we could then claim 10 times 1000 hours or 10,000 unit-hours as before, and the same statement on confidence as before. But now we know that our statement on confidence for the whole system must also apply. Because so often we need test results as early as possible to allow time for design improvement should the reliability be insufficient, we are often forced to make sub-system tests long before we are able to make system tests. To better understand these seeming paradoxes, let us examine the way in which reliability, MTBF, λ, and confidence combine in going from the parts to subsystem level, or from sub-system to system level.

Combining Reliabilities

While fundamental reliability training has taught us that reliabilities of series elements combine by product rule (and thus unreliabilities if very small are approximately additive), failure rates under similar conditions are additive, and MTBF's must be inverted to failure rates to be combined, training often fails to note that all such combinations are to be performed with "best estimate" values. The statistician may mootly consider values for zero bias, values of maximum likelihood, and values which are equally likely to be too high as too low. In any case, the engineer should compute the best estimate by dividing the unit-hours of observation by the number of failures observed (unless the test was concluded upon occurrence of the last failure which then can be ignored) for a best estimate of MTBF. He should divide the number of successes by the total number of trials (successes plus failures) for a best estimate of single-shot or cyclic reliability. If he observes no failures over a period (measured in time, cycles, or trials) equal to or longer than that period which would apply were the test being applied to the overall system, then he should assign infinite MTBF or unity reliability to the sub-system. In any case the observation period should equal (or exceed) for the sub-system that which would have been chosen for the complete system had it been possible to test the complete system instead. For example, if a system is composed of a single unit A, and three unit B's, and would be tested if available for 1000 hours to develop adequate confidence in the desired reliability, then by sub-system test a minimum of 1000 unit-hours should be observed on unit A and 3000 unit-hours on unit B. If one failure were observed on unit A during its test period, and no failures were observed on unit B during its 3000 hours of test, then an MTBF of 1000 hours for unit A should be employed in system reliability computation, and an infinite MTBF for each of the three unit B's. Thus the system computation would yield a 1000 hour MTBF for the complete system, as a best system estimate.

Combining Confidences

Suppose the failure rate of a module consisting of two parts was desired. Part A was known to have a failure rate of 0.2% per 1000 hours with 60% confidence, and part B was known to have a failure rate of 0.092% per 1000 hours with 60% confidence. Is it proper to add the failure rates, 0.2 + 0.092 = 0.292%/1000 hours, and if so is the confidence 60% on the total thus obtained?

Actually none of these failure rates is a "best estimate" rate, as each is pessimistic in order to permit added confidence. We do not have enough information in knowing only the failure rate at a single particular confidence to permit us to determine best estimates nor to permit us to determine resulting confidence in a summation. However, if we can obtain further information, all the desired parameters may be calculated.

We find that the failure rates at 60% confidence were obtained from observing one failure during test of part A and zero failures during test of part B. Reference to Molina's Table II[3] shows a probability, P, of observing two or more failures (observing more than one failure, which is equal to a confidence of P for one failure) of 0.60 if $a = t/\text{MTBF} = t\lambda = 2.0$. For zero failures we find P, the probability of observing one or more failures (probability of observing more than zero failures) is 0.60 if a = 0.92. Simple arithmetic shows both parts were each tested for one million part-hours. One failure in one million part-hours for part A gives a best estimate of 1.0×10^{-6} or 0.10%/1000 hours. Best estimate for part B for which zero failures were observed is zero failure rate provided no more than one million part-hours per end system are required per mission. If this restriction is met, the best failure rate estimate for the module is 0.10%/1000 hours.

If test of each part for a million part-hours could be considered essentially the same as a module test for one million module-hours, with a single failure resulting from this module test, then we already know for P = 0.60 and one failure that a = 2.0, so we have 60% confidence that the module failure rate is not greater than 0.20% per 1000 hours. Note that this is significantly less than the sum of the separate part failure rates at 60% confidence (0.20 + 0.092 = 0.292 % per 1000 hours). Further, reference to Molina's Table II[3] for a=2.9 shows we have 79% confidence that the module failure rate is less than 0.29% per 1000 hours. These data are tabulated herewith for comparison:

$x10^5$ C=60%	From Test f	t	From Tables a	Best Estimate
Part A 0.2	1	10^6	2.0	0.1 $x10^{-5}$
Part B .092	0	10^6	.092	0
Total $0.292x10^{-5}$				0.1 $x10^{-5}$
Confidence for related total 79%				(26%)

total for 60% C = 0.20 x 10^{-5}

A second example which illustrates confidence calculations using the Binomial Tables[4] might be the following. Two units make a system, unit A and unit B. One hundred trials of unit A produce two failures for a best reliability estimate of 0.98, while one hundred trials of unit B produce ten failures for a best estimate of 0.90. The best reliability estimate for the system, assuming failures are independent and all twelve would have occurred in 100 system trials is 0.88 and this figure can be obtained either by computing system success to trial ratio, (100-12)/100 = 0.88, or by multiplying the best reliability estimates of the two units together, 0.98 x 0.90 = 0.88. For 90% confidence calculations, the binomial tables[4] are searched for n = 100, P = 0.90, and r = 3 (more than 2 failures for unit A) to find p (which is the probability of failure of a single unit and equals one minus the single unit reliability) equal to 0.053 (and hence R = 0.947 for unit A). For r = 11 (more than 10 failures) p = 0.15 (and hence R = 0.85 for unit B). For n=100, P=0.90, and r=13 (more than 12 failures as applicable to the combined system) p = 0.17 to give a 90% confidence system reliability of 0.83. If we combine the 90% confidence values for the separate units, 0.947 x 0.85 = 0.80, and look up n=100, r=13, and p=1-0.80=0.20, we find P = 0.97 to give 97% confidence in the 0.80 figure. These data are tabulated herewith for comparison:

	Test Trials	Failures	Rel. Best Estimate	Reliability for C=90%
Unit A	100	2	0.98	0.947
Unit B	100	10	0.90	0.850
System			0.98x0.90 = 0.88	0.947x0.850 = 0.80
Related Confidence				97%

For 90% Confidence, System R = 0.83

A third example may be useful in illustrating that sometimes there is considerable value in low confidence levels. Suppose a system is composed of ten different sub-systems, each of which coincidentally has a best estimate MTBF of 1000 hours to give a system best estimate of 100 hours. Now a system test of 1000 hours duration yielding ten failures is a fairly solid test as established by 90% confidence that the MTBF is at least 64.5 hours. (Molina's Table II[3], P=0.90, c=11, a=15.5, and MTBF = 1000/15.5=64.5 hours.) To make separate sub-system tests, 1000 hours of testing for each would yield the same quantity of total data, but on the average each sub-system would encounter but one failure. The sub-system confidence applicable to a 645 hour lower limit MTBF based on a one-failure 1000 hour test, is found to be 46% (a=1.55, c=2, P=0.46). Thus no more than 46% confidence on each of ten sub-systems is sufficient to yield 90% confidence in the combined system in this particular example.

In general, a unit-hour testing or observation period sufficient to produce desired confidence in a system, is also sufficient to produce adequate confidence in each sub-system provided all sub-systems are tested for this period. Had the last example been the same system but composed of ten identical sub-systems, then the latter's test would have produced 10 times 1000 or 10,000 sub-system unit-hours and ten failures, and would have established 90% confidence in 645 hours MTBF for the sub-system, and it would not be sufficient to test but one sub-system for 1000 hours and observe one failure. As many failures, in general, must occur via combined sub-system tests as would be expected during a system test in order that the lower sub-system confidence be sufficient for a high system confidence.

The examples for confidence combination have in each above example prescribed sub-system or component test or observation periods equal in length to each other and to that for the combined system. If test data are available for the various sub-systems but have been collected over periods of varying length, then common logic permits us to reduce by interpolation all data to equivalent periods equal in length to the shortest period represented. A somewhat more sophisticated technique than described herein for yielding a more optimistic lower confidence limit for system reliability from equal tests of subsystems is described in recent literature by Garner and Vail[5]. This method is not considered applicable in view of the aforementioned rule to count separately independent failures even when occurring coincidentally. To this writer's knowledge, equivalent work using subsystem data from tests of unequal duration has not yet been published.

Planning Tests for Estimation

In planning tests or observation periods for making reliability estimates the important factors to consider are the following:

1. Duplicate or simulate the environment (mechanical, electrical, thermal, etc.) under which the quantitative reliability is desired. The accuracy of simulation may significantly affect the result.

2. Duplicate or simulate the interconnections (mechanical, electrical, etc.) between the unit of interest and associated items or systems, power sources, etc. The proba-

bility of failure from outside cause may be important in the result.

3. Duplicate or simulate the internal environment within the unit to be measured with respect to level of operation (or non-operation), duty cycle, and operator activities and adjustments. The effectiveness of this may importantly control failures from inside causes. Also, remember oftentimes a unit will have different reliabilities for different modes of operation.

4. Unless reliability interest is confined to a specific hardware item and this is the item to be tested, carefully consider the advisability of simultaneously testing (or observing) two or more units so that risk of findings based on a non-representative unit is eliminated. The greater the number of items under observation the less elapsed calendar time required for a given degree of confidence.

5. Plan the total number of unit hours of observation needed, based on desired reliability and confidence. See subheading "Probability and Confidence". If the results are less favorable or unfavorable there will be even higher confidence in the unfavorable reliability. If the tests or observations are to be of all of the separate pieces which will go together to make up a system, there need be no more observation separately than there would be collectively for the assembled system, even though increased MTBF requirements for the sub-systems or parts appear to preclude high confidence with the assigned time for observation.
For example, a system presumed to have 1000 hours MTBF, and with need to establish 500 hours MTBF at 90% confidence is to be tested at the sub-system level. First, the number of failures (f) to be observed to yield a best estimate MTBF (T_0) of 1000 hours and a 90% confidence MTBF (T_{90}) of 500 hours needs determination. If t/f=1000 and t/a=500 where t is observation unit-hours and a is the exponent from Molina's Table II[3] for P=0.90 when c=f+1, then a/f=2 and we find from the table:

a	c	P	page
2	2	0.593994	3
4	3	0.761897	5
6	4	0.848796	6
8	5	0.900368	9
10	6	0.932914	11
12	7	0.954178	14

From this we see a 4-failure test (c=5) is sufficient for 90% confidence in 1/2 the best estimate, and the observation period to be planned should be of 4000 system hours. If the system is composed of one of sub-system A (est. MTBF 12,000 hr.), four series sub-system B (est. MTBF 6000 hr. each), and one sub-system C (est. MTBF 4000 hr.), it will be necessary to acquire only 4000 unit-hours of observation of sub-systems A and C and 16,000 unit-hours for sub-system B. Sub-system confidence from these observation periods, if failures are on the basis of estimated MTBF's are:

Sub-system	Time u-h	Failures	Confidence in MTBF	
A	4000	0	48.8%	6000 hrs.
B	16,000	3	77.9	3000
		or		
B1	4000	1	39.1	3000
B2	4000	1	39.1	3000
B3	4000	1	39.1	3000
B4	4000	0	74.1	3000
C	4000	1	59.4	2000
	4000	4	90.0	500

Planning Tests for Decision Making

The principal difference in the testing rules when testing for decision making is that in addition to the aforementioned concern about test conditions with reference to external environment, interconnections, internal environment, number of units, and duration, it is necessary to establish the maximum number of failures allowed for acceptable equipment.

In the last example of a system producing 4 failures in 4000 system hours of test (or observation) for a best estimate of 1000 hour MTBF, consider the system producer who might be told his system would be acceptable only if it produced no more than 4 failures in 4000 hours of test. Molina's Table II on page 5 shows that with a =4.0 and c= 5 there is 0.371163 probability of more than four failures in this test if MTBF = 1000 hrs., and thus only 1 - .371163 = 63% probability of passing the test. A conscientious producer should demand 90 - 95% probability of passing a test, so he would note that "a" must equal 2.0 for a 94.7% probability of passing, which means his system should, in reality, have an MTBF of 2000 hours. The 5.26% risk of still not passing is called the producer's risk, α , and it is associated with 2000 hours MTBF or Θ_0. The 90% confidence point of 500 hours relates to the 10% user's risk, β , (of less than 500 hours MTBF) and the 500 hour MTBF associated with is usually identified as Θ_1. Thus, a 4 failure test is seen to have a Θ_0/Θ_1 ratio of 4 for α = 5%, β = 10%. Correspondingly, other ratios of Θ_0/Θ_1 for other numbers of failures and for α = 5%, 10%, β = 10% are found to be:

f	c= f+1	α= P	a_o	P	β	a_1	$a_1/a_o=\theta_o/\theta_1$
4	5	.053	2.0	0.900	0.10	8.0	8.0/2.0=4.00
5	6	.049	2.6	0.901	.099	9.3	9.3/2.6=3.58
6	7	.051	3.3	0.898	.102	10.5	10.5/3.3=3.18
7	8	.051	4.0	0.901	.099	11.8	11.8/4.0=2.95
8	9	.050	4.7	0.900	.100	13.0	13.0/4.7=2.75
9	10	.049	5.4	0.900	.100	14.2	14.2/5.4=2.64
10	11	.051	6.2	0.901	.099	15.5	15.5/6.2=2.5
6	7	.101	3.9	0.898	.102	10.5	10.5/3.9=2.7
7	8	.100	4.6	0.901	.099	11.8	11.8/4.65=2.54
8	9	.097	5.4	0.900	.100	13.0	13.0/5.4=2.41
9	10	.098	6.2	0.900	.100	14.2	14.2/6.2=2.3
10	11	.098	7.0	0.901	.099	15.5	15.5/7 =2.22
12	13	.097	8.6	0.908	.092	18.	18.0/9.5=2.1
13	14	.102	9.5	0.901	.099	19.	19.0/9.5=2.0
14	15	.100	10.3	0.895	.105	20.	20.0/10/3=1.94

At this point, it may be observed that as in reliability estimating where two values of reliability and two associated levels of probability are needed to sufficiently identify a measurement (e.g. reliability for 90% confidence and reliability for best estimate), in reliability decision making there are also requirements for two values of reliability and two associated levels of probability or risk (e.g. reliability at producer's risk and reliability at user's risk). In each instance, the four parameters tie down the quantity of data needed for the estimate or decision.

However, for reliability decision making, the sequential test procedure has been exploited as a means for reaching decisions with the same levels of risks with less data on the average. This decision making technique is employed by Tables 5.1 and 5.2, Reliability Accept-Reject Criteria, of Military Specification MIL-R-26667 (USAF), General Specification for Reliability and Longevity Requirements, Electronic Equipments. For Table 5.1, $\theta_o/\theta_1 = 2$ and $\alpha = \beta = 10\%$. For Table 5.2, $\theta_o/\theta_1 = 1.5$ and $\alpha = \beta = 10\%$. The average number of failures to reach a decision in the Table 5.1 test, if the MTBF is that value which will most greatly prolong the test, is 10.2 failures (as compared with 13 in the common procedure) but will reduce greatly for values of MTBF much higher or lower. Similarly, the average number of failures for a decision under the same conditions for the Table 5.2 test is 30 failures. If a sequential test is designed for $\theta_o/\theta_1 = 10$ and $\alpha = \beta = 10\%$, then the average number of failures to decision for the most prolonging MTBF is approximately one failure.

If maximum producer's protection is desired, we can set $\alpha = 1\%$, $\beta = 10\%$ and $\theta_o/\theta_1 = 10$ and find maximum average decision at 4.5 failures. The formula for the average number of failures to decision for the most prolonging MTBF is:

$$E_\theta(r) = \frac{(\ln \frac{1-\beta}{\alpha})(\ln \frac{1-\alpha}{\beta})}{(\ln \theta_o/\theta_1)^2}$$

where ln represents $\log_e$, the natural logarithm. Other sequential test formulas are shown in Fig. 1.

Early consideration resulted in the recommendation that procurement requirements always be specified in terms of the reliability associated with the producer's risk, and that design always be capable of tolerating the reliability associated with the user's risk. The continual desire to push the R and D frontier then forces ratios of θ_o/θ_1 which are close to unity and which then require extended test or observation periods. Means are then sought to avoid the testing all together, or ignore the penalty associated with accepting large risks. Better understanding and publicizing of the complete set of parameters needed to specify reliability will perhaps force more of the engineering profession to recognize this problem and adopt greater discipline in the future.

References

1. Advisory Group on Reliability of Electronic Equipment, Reliability of Military Electronic Equipment, Office of the Assistant Secretary of Defense (R & E), 4 June 1957, p. vii.

2. Burnett, T. L., "Truncation of Sequential Life Tests", Proceedings Eighth National Symposium on Reliability and Quality Control, Washington, D. C., January 1962, pp. 7-13.

3. Molina, E. C., Poisson's Exponential Binomial Limit, Van Nostrand, New York, 1942.

4. Staff of the Computation Laboratory, Tables of the Cummulative Binomial Probability Distribution, Harvard University Press, Cambridge, Mass., 1955.

5. Garner, N. W., and Vail, R. W., "Confidence Limits for System Reliability", Military Systems Design, September-October 1961, pp. 24-27.

SEQUENTIAL TEST FORMULAS

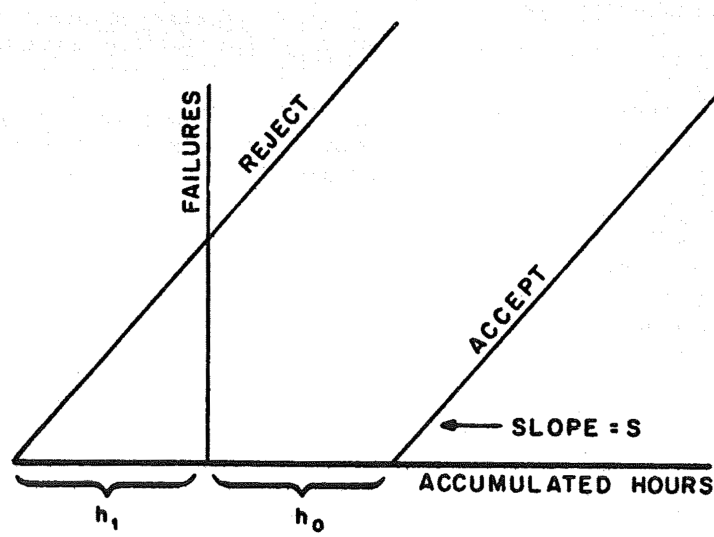
$$h_o = \frac{-\ln B}{\frac{1}{\theta_1} - \frac{1}{\theta_o}}, \quad h_1 = \frac{\ln A}{\frac{1}{\theta_1} - \frac{1}{\theta_o}}, \quad s = \frac{\ln \frac{\theta_o}{\theta_1}}{\frac{1}{\theta_1} - \frac{1}{\theta_o}}$$

$$A = \frac{1 - \beta}{\alpha}, \quad B = \frac{\beta}{1 - \alpha}$$

$$P_{(\theta)} = \frac{A^h - 1}{A^h - B^h}, \quad \theta = \frac{\left(\frac{\theta_o}{\theta_1}\right)^h - 1}{h\left(\frac{1}{\theta_1} - \frac{1}{\theta_o}\right)}$$

$$E_\theta(r) = \frac{h_1 - P_{(\theta)}(h_o + h_1)}{s - \theta}, \quad \theta \neq s$$

$$= \frac{h_o h_1}{s^2}, \quad \theta = s$$



SERVICE EVALUATION OF WEAPONS SYSTEM RELIABILITY

Captain Mark W. Woods, U. S. Navy
Operational Test and Evaluation Force
Norfolk 11, Virginia

Quoting from Webster's Dictionary "Reliable is applied to a person or thing that can be counted upon to do what is expected or required." This is precisely the attribute that the Navy and the other services look for in a missile weapons system. Evaluation of a missile weapons system to determine reliability after it is delivered to the fleet is a very difficult problem. It is particularly so these days when we are trying to reduce lead times in the introduction of new equipments into service use. This process inevitably leads to shortcuts in testing all along the line. There is seldom time during development and production for enough repetitive testing of components, equipments, and assembled systems to get a real measure of reliability or to be certain all design problems have been solved. Consequently, when the first of a new ship class with a new missile system reports to Commander Operational Test and Evaluation Force (COMOPTEVFOR), it in many cases is not sufficiently debugged to be ready for comprehensive reliability testing. Nevertheless, the necessity for immediate commencement of some measure of reliability is essential. The reason is that follow-on ships will be joining the operational forces while COMOPTEVFOR is still testing the first ship, and the tactical commanders must have some knowledge of what performance to expect. This means that even during debugging and shakedown testing, the Navy must exert every effort to commence obtaining reliability data while identifying and correcting problems due to inadequate design, incorrect installations, insufficient personnel training or lack of documentation and spare parts. As any statistician will vociferously testify, this is extremely difficult to do.

The initial efforts then, to measure reliability of a new missile system at sea, commences with the first unit. The quality of these measurements improves as the ship proceeds through the several types of tests and evaluations under COMOPTEVFOR and as the various problems are solved. These tests, in the case of a surface-to-air missile system, might include a Development Assist Test, a Technical Evaluation, and finally an Operational Evaluation. In a Development Assist Test, COMOPTEVFOR assists the Navy Bureau of Weapons (BUWEPS) in final isolation of, and correction of, design problems. The Bureau has technical direction of the project and COMOPTEVFOR controls and coordinates the operation of the fleet units and services involved. This type test normally has heavy participation aboard from the major equipment contractors. A Technical Evaluation is again a joint BUWEPS/COMOPTEVFOR operation in which the objective is to satisfy both parties that the ship is ready for an Operational Evaluation of the missile system. A mutually agreed upon test plan is used and again there is contractor representation aboard, but their participation is limited so as to determine the readiness of ship's company to maintain and operate the system. The final test is an Operational Evaluation planned and conducted by COMOPTEVFOR. The ship is on its own with no Bureau or contractor help and is put through a rigorous test in the sea operational environment.

The sequence of tests is not always in this order. Sometimes we start with a Technical Evaluation and find it necessary to drop back to a Development Assist to correct unforeseen problems. Other times something new turns up in an Operational Evaluation calling for a modification of proceedings. The important point is that BUWEPS, from the shore establishment, and COMOPTEVFOR, representing the fleet, are jointly attempting to measure system reliability all through the test cycle. In the past we attempted to measure system reliability only in Operational Evaluations, when we weren't faced with the problem of sorting out reliability factors from a large number of troubles due to debugging, design, etc. The current onrush of new ships, however, justifies an attempt to accumulate reliability data earlier in the service at-sea testing process.

It is not meant to imply here that component reliability testing does not occur during development and production, or during BUWEPS testing on the firing ranges at White Sands, at China Lake, and from the test ship NORTON SOUND. Since, however, the Navy has not been able to afford preliminary test of complete tactical systems ashore or in R&D ships, all elements of the system ready for evaluation in the sea environment appear together for the first time on the first new operational ship. It is the reliability of this combatant ship and its missile system that is of vital concern to the fleet.

Before going into test program details, a few words are in order on the sea environment.

It is obvious to you all that ships will roll, vibrate, steam in all kinds of weather, and have almost as many sailors on board per square foot as college men in a telephone booth. These factors certainly affect operation and maintenance requirements. What may not be so obvious, however, is how stack gases eat holes in plastic coverings on pressurized wave guide, how the computer which worked fine on your factory floor at 85 degrees ambient temperature overheats in the same room temperature when jammed into the corner of a ship's compartment, how the working and heaving of a ship's structure affects alignment of radars, how the shock of a fighter aircraft landing on a carrier deck affects an air-to-air missile carried in the plane, and how cramped or exposed spaces restrict the number of men who can work on a piece of equipment. We always manage to solve these problems eventually for a particular system, but what is frustrating is that in many cases we have to solve them all over again for new systems. Any contractor providing Navy equipment must be cognizant of how these elements of environment could effect the reliability of his equipment.

This environment also affects our methods of measuring system performance. In the first place, there isn't much room on board so we can't carry large disinterested observing teams. The majority of the data must be recorded by ship's force. This means the requirements must be reasonable and not unduly interfere with other duties. It means there must be some cross checks built into the procedure to identify incorrect data. It means adequate instrumentation must be included to evaluate system and missile flight performance. And finally, it means that when we have an equipment breakdown, we must be able to make repairs in all types of weather and stormy seas, if possible, and with the spares we can carry on board.

In setting up an evaluation program for a new ship in the sea environment, we have many objectives besides determining reliability. As mentioned earlier the Development Assist Tests and the Technical Evaluation are primarily for debugging and certification of readiness for the big test which is the Operational Evaluation. In a few words, the objective of the Operational Evaluation is to determine readiness of the system for war. Since this test is usually longer and involves more firings than previous tests, we often uncover additional design and installation problems. Obviously, we continue to measure reliability. We also measure efficiency and adequacy of logistic support and of personnel training and manning levels. This includes not only firing exercises but non-firing tests of such things as resupply of missiles at sea from ammunition ships. Hundreds of hours are used in measuring radar detection capabilities and target processing time starting from single raids up to and including mass saturation attacks.

Missile firing tests are always limited by the availability of missiles. There are never enough missiles to optimize tests throughout the envelope strictly for reliability purposes. To do this requires several shots at a given target under almost identical performance conditions in order to be able to state reliability with a high level of statistical confidence. Remembering that this is the first ship of a class, there are still unexplored areas of the performance envelope. During earlier RDT&E testing we are usually restricted for safety considerations in what can be done on the land range. The R&D test ship normally does not have the full tactical system. Consequently, of first priority will be conduct of those tests which couldn't be done anywhere else. This not only includes several new missile flight trajectories, but conducting the shots with such added attractions as high ship speed, high roll, guns firing, etc. It also includes all the different possibilities of the target presentation in combat such as varying speeds, altitudes, and maneuvers. Every effort is made to eliminate unimportant variables and to combine tests so as to contribute the maximum amount of data for statistical reliability purposes. The order of tests is also randomized as much as possible in order to eliminate unpredicted effects of time.

Throughout the entire test program we must be extremely careful that we don't identify unreliability when in truth the problem is more due to inexperienced personnel, unavailable spare parts, improper documentation and procedures, or just plain unrealistic requirements in the sea environment. But we have to be just as careful on the other side of the coin to resist the siren song of some contractors saying that if we will just train our men to the level of engineers and buy enough spares our problems will be solved. Obviously we will never be able to train all our men to be systems engineers. Nor will our logistics system support great quantities of spares. One reason the Navy insists on conducting Operational Evaluations with fleet ships under COMOPTEVFOR is that fleet personnel have the most realistic appreciation for our reasonable capabilities in training and logistic support.

As a final comment on the test program, it is important to understand that much of our support comes from fleet units and activities.

This is true for all our tests at sea whether for a Development Assist Test or an Operational Evaluation. Since these units and activities do much more than support our test and evaluation operations, efficiency in the use of services is essential. These services must be scheduled months ahead of time and are not easily responsive to last minute changes. Let me urge then that any of you, whether service or contractor personnel, who find yourselves involved in tests at sea do the very best advance planning you possibly can to take advantage of fleet services when scheduled.

Let me now go into some detail on how the Navy measures reliability in the TALOS, TERRIER and TARTAR Surface-to-Air missile systems. As implied earlier, we don't stop measuring reliability on completion of OPTEVFOR tests. We must continue to measure reliability and readiness throughout the service life of the missile system on all ships. This requires that the measurement procedure be the same on all ships if we are to get any meaningful statistics. The procedure must also be broad enough to provide the needs of all the interested activities such as COMOPTEVFOR, the Navy's Technical Bureaus and the Fleet Commanders. The detailed methods we used a few years ago when we had only a small number of missile ships are not now equal to our needs. We have learned a lot from the many ships which commenced joining the fleet last year. As a result of a rather long study, with inputs from the many interested activities, the Bureau of Weapons and the Bureau of Ships have recently published a revised Standard Reporting Procedure for Surface-to-Air Missile System Operability and Maintenance. This procedure will be used by all surface-to-air missile ships whether in the test and evaluation status or in fleet operations. Modifications to suit the needs of a particular activity will be by addition and not deletion of any of the requirements.

The overall system includes reporting in the following categories:

a. Component Failures.
b. System Material Operability and Maintenance.
   (1) Missiles.
   (2) Non-expendable Equipment.
c. Missile Firings.
d. Commanding Officer's Quarterly Narrative Reports.

Items a through c are reported on with forms provided to the ship. Item d, the Commanding Officer's Narrative, is a letter report covering anything else in addition that the Commanding Officer feels is pertinent but must include a short summary of his operations, overall weapons system appraisal, spare parts adequacy, system documentation adequacy, personnel status, outside technical assistance requested and received, plus any recommendations.

Component Failure and Missile Firing Reports are filled out and mailed to prescribed activities when occurring. Although these are officially compiled and analyzed by designated organizations, all appropriate contractors may receive copies of failure reports and all appropriate missile ships and fleet commands receive direct copies of firing reports. The System Material Operability and Maintenance reports on Missiles consist of results of periodic missile systems tests of the depot stockpile and ships magazine loads. These reports are compiled and analyzed by the same agency that analyzes flight tests.

I would now like to go into some detail on the System Material Operability and Maintenance Reports of Non-Expendable Equipment. Here is where we get a feel for the readiness or reliability of the installed support equipments such as search and detection radars, fire control radars, computers, etc. The report makes use of the following formula:

$$Pe = Pa \times Pr$$

where;

Pe = System Material Effectiveness Factor expressed as a decimal or percent.
Pa = System Availability Factor.
Pr = System Reliability Factor.

The Pa, Availability Factor, is based on the scoring of a Daily Systems Operability Test (DSOT) and is the average score obtained over a month's period. The DSOT consists of a complete dynamic test of all major elements when operating together as a system. It is the best test that can be devised which can be run in a reasonable period of time, say 1/2 hour, to give high assurance that the system is ready for use. The score is determined by a formalized procedure and is a function of how long it took the ship to pass the test correcting any deficiencies found. As many DSOTs can be run as desired either on a planned or surprise basis, they all count on the monthly average score.

The Pr, Reliability Factor, takes care of what we might expect the system reliability to be between DSOTs. It is a function of the mean time between breakdowns "T" anywhere in the system and the interval "I" between DSOTs. These are figured over a month's basis and the

ship computes a function $\bar{T}/I$. Using $\bar{T}/I$ and a graph provided by BUWEPS, a value is obtained for Pr. The graph is based on predicted failure rates of components with time. The longer the measured interval between breakdowns, the higher the Pr. The shorter the interval between DSOTs, at which time the system is known to be operational, the higher the Pr score. The Pr value gives a direct measure of how equipment is performing on a particular ship being directly responsive to that ship's failure rates and testing frequency.

One other important record is required by the ship in order to easily tell why the ship may have a high or low overall Pe, Material Effectiveness factor. The previously mentioned Component Failure Reports could provide this data with enough correlative effort. To have a ready reference, however, another form called the Equipment Status Report is used. This form is kept on each major equipment such as radar, launcher etc. and provides for filling in a status category for each hour of the day over a week's period. The various categories are as follows:

a. Operating at Full Capability.
b. Operating at Reduced Capability. This might include some automatic functions being out of commission but the system is still operating by manual inputs although at reduced firing rate.
c. Undergoing Systems Test.
d. Standby - low voltages applied only.
e. Shut Off.
f. Non-Interruptive Preventive Maintenance. in progress - could still fire if needed.
g. Inactive - ship in Navy Yard, etc.
h. Interruptive Preventive Maintenance in progress.
j. Undergoing Modification.
k. Down - Undergoing Corrective Maintenance.
l. Reduced Capability - Undergoing Preventive Maintenance.
m. Down - Awaiting Spares.
n. Down - Equipment Cannibalized.
p. Down - Failure of Support Equipment - test equipment, ship's power supply, etc.
q. Down - Require Outside Help.

It may appear from what has just been discussed that the Navy will have to man ships with mathematicians and stenographers to use the new Bureau reporting system. It's not quite as bad as it looks since all the forms are provided and it is simply a matter of following instructions. As can be seen, there are some cross checks built into the plan which should help identify bad data. As mentioned before, the plan is based on earlier experiences and evaluations wherein we have, at times, had need for all the data now required. Certainly, the new procedure will require a serious and time consuming effort on the part of the ship's company. There isn't any doubt in our minds that our ship's personnel are equal to the task or that this effort is essential to a valid prediction of combat capability.

In conclusion, let me emphasize that the objective of testing, in the sea environment is to simulate in peacetime, all the requirements we can foresee during war, -- to give everthing a chance to happen that could happen. It is this requirement that dictates continuous efforts to record and analyze reliability data at every opportunity in the formal testing cycle of new systems as well as during subsequent operations of all fleet units. The real pay off and the toughest part of the job comes in the analysis and formulation of conclusions. Decisions on how to improve reliability are usually the most difficult to formulate in the marginal cases; that is, in those situations where any one of several feasible courses of action might suffice, such as more comprehensive personnel training, a larger stockpile of parts, or a redesign of some component. Obviously, pursuance of all three is the best solution. However, efficient use of manpower and funds usually dictates otherwise. The talents and brains, objectively used, of the whole Service and Industry team are required if these decisions are going to be timely and correct. The best practice in Industry, of course, is to design and build reliability into equipment in the first place, to give reliability just as high a priority as performance. Highly reliable defense products not only promote individual company reputations, but the greater welfare of our Nation as well. In the Services we also have work to do in the continuous examination of our specifications, and the stating of our needs as precisely as possible. Only by such an enlightened, combined effort can we buy with out dollars the "BANG" we can count on when our sailors, soldiers, or airmen close the firing key.

RELIABILITY TECHNIQUES IN PRODUCTION

B. L. Lubelsky
Lockheed Missiles and Space Company 524070
Sunnyvale, California

17269

Summary

When discussing "Reliability" activities, I am including all special functions devoted principally to enhancing total product quality--and those functions known as quality control and/or inspection are, of course, of major importance in production areas. In addition, while the Reliability engineering activity has largely been identified with the design activities, the production of reliable hardware in conformance with approved engineering designs is also a Reliability engineering area of effort.

Design Definition Review

1. This function can be classified as either one of the end functions of the design phase or as one of the starting functions of the production phase.

2. The purpose is to make sure the designer's intent is fully and completely communicated to the technicians who will convert it into hardware and to the inspectors who will test and inspect it.

Manufacturing Paper Review

Most people not closely connected with production activities, and this includes most designers, are under the illusion that manufacturing people work directly and only from the engineering design.

1. Production activities have their own special "family" of planning and process paper which is used to convert the engineering design into the detailed instructions necessary for manufacturing. This may include substituting "equivalent" standard manufacturing process specifications for the design-produced process specifications. While these manufacturing specs may start out as "equivalents," changes and necessity may soon cause significant differences.

2. Reliability engineering review of the production planning and process paper to assure its compatibility with the designer's intent is one of the more important production reliability activities. This is done on a sampling basis with unsatisfactory areas receiving further detailed investigation.

Manufacturing Production Planning

This Reliability area includes both general requirements, such as cleanliness and good lighting, and detailed requirements relating to material flow, work station layout, process equipment and control, material handling, packing, and many others.

1. Reliability review of production planning, while it is still planning, often discloses conditions which are not favorable toward the consistent production of reliable hardware. Such unsatisfactory conditions, such as failure to provide for a "clean room" for production of delicate electronics equipment, can be forced to general management attention so that the deleterious effects on production reliability are appreciated and considered in reaching a final decision.

2. Continuing review of production practice changes is also necessary as a change which may appear to be desirable for economy of time or money is often detrimental to reliability and may, in final balance, cause extra costs rather than achieving savings.

3. Independent outside audit of chemical process specifications may sometimes be required to ascertain whether or not the specified process will, in fact, produce the plating, painting, anodizing, welding or other result required.

Test and Inspection

This is the big area of quality control--the job of measuring hardware dimensional and functional characteristics, comparing them with the design requirements and recording the results. Statistical tools such as lot sampling and show-how process charts may be of value in this area--particularly if volume is large and automatic test/inspection equipment is not used.

1. While "inspector" seems to be a depreciated word--this is the area of test and inspection by an "inspector." Certain quality functions such as test and inspection planning are required to assist the inspector and certain data handling techniques are useful in identifying trouble areas not immediately apparent during normal inspection operations.

2. As "check and balance" is one of the basic premises behind Reliability activities, an audit of quality control planning, procedures and activities is required.

3. Failure diagnosis by engineering (design, reliability and production) personnel to determine primary failure causes on both

factory and field failures will speed effective corrective action (design, production or procurement) to prevent continuous recurrence of the failure mode.

4. Participation in Material Review activities to assure against unacceptable material getting used is also a very important production quality control function.

Conclusion

I have just described to you some of the major product quality functions in the production portion of the design-produce-use chain. Under tactical production situations a repair/overhaul cycle on field-returned material is a separate portion of the production activity which must receive special attention in all of the previously mentioned areas. As nine hundred and ninety-nine departures from the designer's intent will degrade quality as compared to one or two which might improve it, the production product quality function is to insure and assure full design conformance.

ECONOMIC CONSIDERATIONS OF RELIABILITY

F. E. Wenger
AFSC, Andrews AFB, Md 22508

The subject of this presentation "Economic Considerations of Reliability" is like trying to put a value on life or freedom, for this is just what the reliability of our systems means to us. The purpose of this speech is to stimulate thinking and action, not to give all the answers. The barrier which I am trying to overcome is not heat or sound but that of mind; this appears to be the only barrier man is confronted with anyhow. We must not be limited by mental blocks, such as -- we cannot use this reliable part because it costs 15 cents more than a conventional one, and we cannot stand the extra cost. This statement, on a 50 million dollar or 100 million dollar program -- a part failure can cause an abort at the launching site at a cost of millions of dollars, plus an exhaustive search for similar defective parts in other systems, which is more costly than all the parts used in the equipment.

Thousands of words have been written on reams of paper on how to increase reliability, but all this has accomplished is to demonstrate that you cannot solve the reliability problem by oratory, any more than you can clear a traffic jam by blowing a horn, and the best reliability program is useless unless there is someone to bundle up the reliability requirements in the program and turn over reliable equipment to the customer. How good a job you, the producer, have done is determined when we, the customer, use it.

We hear a great deal about the cost of Reliability, but I would like to make a categorical statement that Reliability does not increase cost, but the achievement of realistic reliability figures pays in dollars, in time, and above all, in systems effectiveness or readiness. I would like to pose a question to you -- if you had a million dollar metalworking machine that was vital to your survival, and its reliability was 33% and its availability only 3 hours out of 24, at a maintenance cost of $1,000 per day -- would you hesitate to spend another $250,000 to achieve 90% reliability with an availability of 20 out of 24 hours and a maintenance cost of $50 per day -- your answer would be, let's get on with the program.

To stimulate your thinking and to illustrate the savings that can accrue in a total reliability program, I have chosen a few representative examples of what can be achieved.

Savings are defined as money not spent for maintenance of a system due to increased reliability. I will also illustrate how total cost reduction can be achieved through increased availability of a system.

The tremendous savings of money that reliability (properly used) can achieve for the military is almost unbelievable. The first example will be concerned with a simple electron tube -- not much chance for cost reduction here -- well, let's see.

The 5814 type electron tube is presently issued at the rate of 800,000 per year to Air Force operational forces. These are replacement parts; each one represents a maintenance action and all of the logistics actions associated with a maintenance action. A review of the cost to the Air Force of removing an equipment from an aircraft, and/or missile, checking of the equipment, removing and replacing the defective part, realigning the equipment, and reinstalling the equipment into the systems, shows a cost of between 5 and 353 dollars.

For the purpose of this illustration, I will use the lowest figure of $5.00 per maintenance action. Let us assume that we can buy this tube at various reliability levels as shown on this slide.

SLIDE 1

FAILURE RATE	COST/ITEM
1.%/1000 hrs	$1.00 present practice
0.1%/1000 hrs	$3.00 (hypothetical fig)
0.01%/1000 hrs	$9.00 (")
0.001%.1000 hrs	$27.00 (")
0.0005%/1000 hrs	$50.00 (")
0.0001%/1000 hrs	$100.00 (")

SLIDE 2

This slide shows relationships between failure rates, the number of tubes needed per year, maintenance cost at $5.00 per maintenance action, total tube cost at each failure rate. This cost is based on a hypothetical tube. As you know, tubes with such low failure rates are not available as yet.

The cost of buying this tube under present practices is $800,000 and the cost of maintenance action to replace this tube at $5.00 per maintenance action is $4 million (startling isn't it!) so the total cost to the Air Force is 4.8 million dollars.

I am going to hold this slide for a few moments to give you time to digest its import. I stated at the beginning that I wanted to stimulate thinking. This should do it, but more important, reliability techniques and procedures can be applied to show real progress in cutting expenditures.

In passing, it is worthy to note that we could pay $11,995 for a single tube having a failure rate of 0.0005%/1,000 hrs without increasing present expenditures.

The next example will be concerned with an equipment, specifically the 412L system. This system is composed of 13 subsystems (AN/GPA-73) whose parts complement, added together, total 8 million semiconductors and 30 million other electronic parts. This is greater than the total number of electronic parts found in a modern city of one million inhabitants, counting all radios, television sets, transmitting stations, the telephone system, phonographs, amateur radio systems, radio operated garage door controls, etc. In addition, the basic 412L system is associated with data acquisition equipment which contains an additional estimated 882,000 electronic parts, a communications Subsystem with an estimated 2 million parts and ancillary equipment totaling an estimated 500,000 parts. This adds up to 41,382,000 electronic parts in the complete 412L system.

The complexity of the 412L system poses a severe reliability problem. In June 1959, the formula of paragraph 3.2 of MIL-R-26474 was utilized to compute the reliability of one AN/GPA-73, hereafter called subsystem (without consideration of the data acquisition, communications or ancillary equipments). This formula, which reflects the state of the art (i.e., that reliability obtainable without the use of special parts, extreme derating, etc) predicted that the system would experience 28,500 failures for each 10,000 hours of elapsed time.

In January 1960 another prediction was made which considered the derating and cooling which would be applied to the parts, and a prediction of 13,092 failures per 10,000 elapsed time hours was made. This is, of course, still greater than one failure an hour. The contractor then embarked on an aggressive reliability program which included the generation of specifications for special high reliability parts.

In January 1961, a Monte Carlo simulation of the subsystem operation was made incorporating the latest expected part failure rates, and the results indicated a reduction of the failure rate to about 155 failures per 10,000 hours of elapsed time. It should be noted, this prediction eliminated part failures which would not cause system failure. This would cause the improvement to appear greater than it really is. This was taken into consideration by allowing an adequate safety margin in our computations. The 412L system, (considering only the 13 AN/GPA-73s) will cost an estimated total of $195,000,000. Government furnished equipment and site construction will double this figure. The reliability program cost - $1.46 million.

In considering the economies of the program, however, many viewpoints may be taken with varying advantages and risks. Three of these viewpoints will be discussed.

The first economic viewpoint will consider monetary considerations exclusively, and will assume a ten year equipment life. It was previously shown that the difference in the 1959 and 1961 reliability predictions is 28,345 failures per 10,000 hours. Adding a safety factor to compensate for the fact that the 1961 prediction included only functional failures, it is estimated that 28,500 failures/10,000 hours would occur under the 1959 predictions and 500 failures/10,000 hours for the 1961 prediction with the safety factor previously mentioned. Using the $5.00 maintenance costs, which is way low, there would be a $140,000 savings per set per 10,000 hours. For the 10 year period using 13 sets, there would be a saving of $15,955,000 due to improved reliability.

Let us look at it another way, the 28,500 failures per 10,000 hours predicted in 1959, when coupled with expected repair rates of 12 minutes for display portions and 6 minutes for data processing portions of the subsystem would have resulted in a total of 2,800 hours of downtime out of every 10,000 hours elapsed time. The figures predicted in 1961 with the same repair time would result in an expected downtime of only 21.5 hours out of every 10,000 hours. This means the subsystem envisioned in 1959 would have been available for duty about 72% of the time. The system envisioned in 1961 would be available over 99% of the time. Applying the safety factor for the difference in prediction methods and using a 90% availability from the 1961 prediction, availability will have jumped from 72% in 1959 to 90% in 1961. This occurred at a cost of reliability of $1.46 million in a $295 million contract, or about 3/4 of 1% of the system cost (not including GFE or site construction). A 0.75% increase in program cost, therefore, bought a plus 18% increase in the availability of each subsystem.

There is still a third method of figuring the economics of reliability. This method is concerned with putting a value on reliability based on cost per hour of operation, the contractor reasons that the cost of the system in 10 years would be 295 million dollars plus the operating costs of $40 million per year or a total of 695 million. This establishes a value for the 13 sets of about 8,000 dollars per hour over the 87,600 hours in the 10 year period. A single subsystem would, therefore, be worth $615 an hour. Therefore, using the 1959 prediction, the subsystem would be out of commission 28% of the time or about 2800 hours per 10,000 hours resulting in a cost of $1,722,000. Using the 1961 prediction, the subsystem would be out of commission 10% of the time

or 1,000 hours per 10,000 hours, resulting in a cost of $615,000 for the downtime period.

Since there are a total of 13 subsystems in a complete system, there would be a dollar savings of $12,840,000 in downtime for an investment of $1.46 million in reliability. This slide summarizes the three methods of evaluating the economics of reliability.

SLIDE 3

An example of simple reliability practices providing comparatively large gains in both reliability and operating economy is provided by a display system now in development. This system contains 3400 indicator light bulbs. To maintain a required failure rate of 1% per 1,000 hours, they must be replaced by preventative maintenance before the wearout portion of their life is reached. Under normal conditions this would require the replacement of each bulb after about 400 hours of operation. At thirty cents a bulb, this would cost the Air Force $1,020 every 400 hours or an operating cost for bulb replacement alone, of about $22,000 each year. By derating the bulbs to operate at 12 volts instead of at the rated 14, the replacement period will be increased by six times. The bulbs would therefore, need replacement only every 2,400 hours, or less than four times a year, for a yearly cost of less than $4,000. $18,000 will be saved each year.

I think it is fitting to close this paper with some figures from a program you have all heard about -- TACAN.

The TACAN equipment, military nomenclature AN/ARN-21, has evolved through models A, B, and finally C. The A and B models were procured without reliability as a specified requirement and were delivered with a mean time between failure (MTBF) of 17.5 hours. The C model was purchased with a 150 hour MTBF requirement. The contractor met the requirement.

The records of the Air Force show that the average cost per maintenance action of the TACAN equipment is $147.00. At 17.5 hr MTBF the cost/year for logistic support is $8,400 per set. Approximately 16,000 sets are in use. The total logistic cost per year is approximately $134.2 million. The C model TACAN at 150 MTBF cost only $980/year to support. The total logistic support cost is approximately $15.7 million/year.

By enforcing the reliability requirement for the C model TACAN, the Air Force is realizing a yearly savings of approximately $118.5 million. This slide shows this support savings on a basis of reliability vs. per set year.

Incidentally, the C model sets having 150 hrs MTBF cost $300 less than the A and B model 17.5 MTBF sets, and has higher performance characteristics.

SLIDE 4

ACKNOWLEDGEMENTS:

The writer wishes to acknowledge the contributions made by Mr. F. Ruther (AFLC) and Mr. A. Coppola (AFSC) to the content of this paper.

SLIDE 2

A	B	C	D	E	F	G	H
Failure Rate	Present Consumption	Predicted Consumption	Maintenance @ $5.00 Replacement	Total Tube Cost	Estimated Item Cost	Total Tube and Maintenance Cost	Money Not Spent
1.0%	800,000	800,000	4,000,000	800,000	$1.00	$4,800,000	
0.1%		80,000	400,000	240,000	3.00	640,000	$4,160,000
0.01%		8,000	40,000	72,000	9.00	112,000	4,678,000
0.001%		800	4,000	21,600	27.00	25,600	4,774,400
0.0005%		400	2,000	20,000	50.00	22,000	4,778,600
0.0001%		80	400	8,000	100.00	8,200	4,786,000

SLIDE 3

1 Set Per 10,000 Hours

	Maintenance Cost \$5/Maintenance Action	Downtime @\$615/hr	Percent of time Available
59	\$142,500	\$1,722,000	72%
61	2,500	615,000	90%
Gain	\$140,000	\$1,107,000	18%
	Total for 13 Sets 24 hrs a day for 10 years		
Total Gain 61-59	\$15,955,000	\$125,840,000	18%

Slide 4

THIS SLIDE SUMMARIZES THE TACAN DATA ON A YEARLY COST BASIS

TACAN

MTBF in hrs	Maintenance	No of sets	Total Maintenance	Savings
17.5	$147	16,000	$134 million	
150	$147	16,000	16.7 million	
				118.5 million

RELIABILITY RESEARCH NEEDS

E. J. Nucci
Office of the Director of Defense Research and Engineering
Washington, D. C.

245180

17271

Summary

Experience in the application of techniques developed through research in reliability has revealed gaps in the technology and areas in which present techniques should be refined or the technology, extended. These deficiencies, representing needs in reliability research, are enumerated, and priorities are suggested for some.

Introduction

In the past decade, much effort has been expended in attempts to gain--or improve--reliability in military weapon systems. The most formally organized and probably the most intensive efforts along this line have been in electronics. I will not confine my remarks, however, to electronics or missiles or any other specific area; I want to talk about weapon-system reliability as a whole.

All past efforts might be considered as falling into three categories: (1) the development of new, improved parts and materials designed to be used in extreme environments and to have longer life; (2) the development of techniques for designing reliability into the end product and for measuring reliability and the improvement of engineering practices; and (3) the application of the new parts, materials and techniques.

Although there have been many gratifying successes in the effort to apply new developments, experience has proved how much remains to be done; we have only scratched the surface. Certain techniques must be refined; there are definite gaps in the technology; and there are areas in which the technology must be extended to cover more extreme situations. These deficiences represent our needs in reliability research. Important as they immediately appear, these objectives gain even greater significance when considered in the light of requirements for advanced systems now being planned--especially those intended for space operations.

Research Needs in Reliability

Categorized in the two major areas of (1) systems and equipment reliability and (2) parts reliability, here are some of the unfilled reliability research needs:

Systems and Equipment Reliability

(1) Refined techniques for predicting reliability of electronic systems

(2) Reliability-prediction methods for mechanical systems

(3) Design methods to ensure specified life for mechanical and hydraulic parts

(4) Self-healing design techniques, such as redundancy; self-organizing or self-adapting systems; self-checking systems; fail-safe tehniques, etc.

(5) Techniques for demonstrating reliability--especially for large, complex systems with long mean time between failures; for expendable systems with a long time to failure, such as satellites; and for costly, expendable systems with a low production base, such as ballistic missiles

(6) Accelerated testing techniques, with acceleration factors correlated to the life or reliability of circuits, assemblies and systems, to reduce cost, sample size and test time in reliability-assurance testing

Work in these six research areas is in addition to basic programs such as the following:

(7) A research and measurement program aimed at gaining a better understanding of the total space environment and determining its effects on materials, component parts, circuits and assemblies

(8) The improvement of techniques for isolating component parts and critical assemblies--possibly entire systems--from extreme environmental conditions imposed by temperature cycling, radiation and acceleration

(9) The development of techniques for sealing and lubrication in high vacuum

(10) The expansion of efforts to develop parts and materials optimized for the space environment and with extremely long life for missions of extended duration

(11) Studies of the human factors in space operations

Parts Reliability

In the area of research on parts reliability, the list of unsatisfied needs continues as follows:

(1) Research into failure mechanisms of electronic, electrical, electromechanical and mechanical parts, with a view to developing analytical descriptions of parts characteristics and life expectancy as a function of use and environment

(2) Development of self-healing parts

(3) Techniques for quantitative prediction of parts reliability--in contrast to predictions based on the results of mass testing; techniques for predicting future characteristics and life based upon (a) physical or electrical inspection and short-term measurements and (b) analysis of the physics of materials

(4) Accelerated testing techniques, with acceleration factors correlated to the parts' life characteristics, the objective being to reduce cost, sample size and test time in reliability-assurance testing

(5) Practical, economical methods of proving compliance with requirements for extremely low parts failure rates (such as 0.001 percent per 1000 hours and lower).

(6) Techniques for reliability-assurance testing of high-reliability items procured in small lots

Again, these six research needs are considered as supplementary to the basic programs for developing long-life parts and materials that are suitable for the anticipated environments in which they will have to serve. Here let me emphasize that the job is not confined to the case of extending the life of conventional parts that are already available; it includes the development of new parts and materials such as those that solid-state electronics may offer.

Analysis of Priority

So far, in my attempt to identify the principal areas in which research is needed, I have indicated no priority ratings. The grouping was based on the two categories of reliability research, systems and parts. Design-oriented items were listed first, followed by those related to the measurement or demonstration of reliability. From a management standpoint, these items should be analyzed with respect to their relative importance. Priority assignments for individual items, however, will differ from one program to another, depending on the criteria established in each for determining urgency. For illustration:

(1) In a long-range program aimed at developing systems that must operate over extremely long periods of time, high priority is given to work on long-life components, self-healing design techniques and the determination of failure mechanisms.

(2) If the immediate job is to develop costly, complex, expendable systems for an extended mission period and only a few are to be built at a time, priority goes to the solution of problems involving small-lots reliability assurance, reliability demonstration, refined prediction and other techniques for analytical design evaluation and self-healing design.

(3) If our goal is to speed up development and cut costs but retain the assurance of reliability, priority falls to the development of accelerated testing techniques, prediction techniques and the shortest and most economical methods of test demonstration and reliability measurement or evaluation.

(4) When the basic need is a formula for specifying reliability in contracts, possibly associated with provisions for incentives or penalties, first priority would be assigned to the development of methods by which reliability can be quantitatively specified and measured.

We could establish still other sets of criteria, but those I have mentioned could be matched to the current situation in our missile and space projects. In summary, we would find ourselves facing the need for (1) developing complex, low-production, long-mission-time systems, (2) demonstrating reliability in complex, expendable systems and (3) cutting costs and shortening development times to meet early operational dates.

This leads me to suggest that the following areas should be given high priority:

Predicting and demonstrating reliability
Accelerated testing
Self-healing design
Assurance of reliability in small production lots

And the effort in these technique areas is to be fully supported by the basic programs for developing new and longer lived parts and materials.

Not everyone will agree with these suggested priorities, for needs vary with the situation.

I ask your assistance in letting us know about new reliability problems that are revealed from day to day. For our part, we are most interested in your efforts, especially those that culminate in whole or partial solutions on which data may be made generally available--to the benefit of the nation's defense program as well as its industry.

Conclusion

Our weapon technology is growing at a tremendous rate, and there are unprecedented demands for performance and functional capability. Moreover, in contrast to former reliability needs, the degree of reliability now required in many cases for successful operation has been multiplied by a factor of 10--sometimes as high as 100.

The very nature of many new systems denies us the use of such established procedures as product improvement and calls for a reorientation of our design philosophy and management. In technical as well as management areas, techniques must advance in order to stay abreast of mission requirements and, at the same time, cope with time scales and allocated budgets.

The successful pursuit of the research needs enumerated will go far toward gaining objectives that are vital to our national defense. A considerable part of this work is now in progress, sponsored by both industrial and government research activities. These programs must be compatible and complementary. Their results should be documented and published for use by all interested agencies of government and industry.

Reliability is the key to advanced weapon technology and success in space operations. In our defense, in our economy and in the prestige we enjoy among the world's nations, it is of the utmost significance that our systems of all kinds function dependably. And it will take the combined efforts of our government and our industry to achieve the required reliability.

THREE LESSONS FROM THE RELIABILITY VERIFICATION PROGRAM

David B. Christian
Light Military Electronics Department
General Electric Company
Utica, New York

Introduction

This paper discusses three important lessons that resulted from a Reliability Verification Program. The General Electric Company builds Radio Guidance Equipment for the Atlas Missile Program. The Mod III A/B equipment is one of the airborne guidance systems that has been designed and built at the Light Military Electronics Department to be used with the ground system built by the Defense Systems Department. The airborne system consists of two beacons and a decoder. Figures 1 and 2 show the equipment set up for vibration testing.

The system operates by sending signals to the ground station. These signals are interpreted by the ground system and a message is returned containing information for missile-course correction. Such a system has two principal advantages: It is precise. It is highly reliable.

The question that arose in 1959 was, "How reliable is this system?" "What is the probability of a successful guided flight?" The minimum acceptable reliability for such a system was 0.925 with 95 percent confidence. From this requirement, the Mod III A/B Reliability Verification Program evolved.

The concept of a test program to verify the reliability of such a system was not new. To design the program, we needed only to make the following assumptions:

1. Assume that repeated vibration cycling of the equipment will not reduce its life.
2. Assume that in the laboratory you can simulate the vibration environment of a missile flight.
3. Assume that the sample used is representative of the population of guidance systems.

On the basis of these assumptions, the program could be designed, the reliability of the system could be determined, and the validity of the assumptions could in turn, be verified. The method decided upon for obtaining failure data was to test six systems to failure under simulated-flight environmental conditions. If the system degrades markedly with continued electronic cycling, or vibration, or both, the first assumption would not hold, and the contractor could be penalized severely. With a sample as small as six, it is extremely difficult to demonstrate with a high degree of statistical confidence whether the failure distribution is influenced by vibration fatigue.

The stated purpose of the Mod III A/B Reliability Verification Program was to:

1. Estimate the reliability of the Mod III A/B airborne equipment during a countdown and flight period.
2. Derive information from which the reliability could be further improved.
3. Verify the feasibility of experimentally measuring reliability.

As stated earlier, the customer wanted to be assured that the reliability of the airborne system was at least 0.925 with 95 percent confidence. The Mod III B Reliability Verification Program demonstrated:

1. With 95 percent confidence, equipment reliability for a countdown and flight period is no less than 0.994.
2. The confidence level at which a 0.925 probability of failure-free operation may be inferred is greater than 99.95 percent.

The program was feasible. The reliability of the airborne equipment exceeded not only the minimum acceptable reliability, but also the design objective of the Mod III A/B Program.

The verification program was concurrent with actual flight test of the Mod III A system. Problem areas indicated by the verification program agreed very well with those brought to light by the ground and maintenance tests of the Mod III A equipment in the field. This correspondence added confidence in the program and with it an urgency and sense of need to eliminate the problems revealed. In this sense, information was obtained that did aid in improving the reliability of the guidance equipment.

This paper presents three significant lessons learned from the Mod III A/B Reliability Verification Program. It discusses the significance of these lessons and how they have affected the planning of subsequent evaluation. It goes on to discuss in a new light what the program has added to our knowledge of the behavior of complex electronic systems.

Briefly stated, the lessons are:

1. This type of Reliability Verifica-

tion Program can and should be a valid means for demonstrating the reliability of a system.

2. There are relationships between time, cycling, and vibration.

3. The time required to perform such a program may limit its value.

First Lesson: Validity of Test Program

The test program was feasible and valid. The program simulated two environments: The first environment was that of the equipment checkout and maintenance period. This environment is comparable to the ground environment before placement of the equipment on a missile for countdown and launch. The second environment is that of missile countdown, launch, and flight operation.

The flight vibration requirements were simulated in accordance with the telemetered data received from Atlas flights. Temperature was controlled so that for each simulated flight each system experienced flight-temperature conditions.

Table I compared the failure rates from the Verification Program's first environment with the actual field experience observed with General Electric's Mod III A/B equipment.

TABLE I
Failure Rate Comparison

FIELD

Unit	Major & Critical Failure Rate	95% Confidence Bands
Pulse Beacon	0.0032	0.00184 - 0.00483
Rate Beacon	0.0023	0.00144 - 0.00382
Decoder	0.0034	0.00202 - 0.00502
System	0.0089	0.0063 - 0.0113
System Mean-Time to Failure	112.3	

VERIFICATION PROGRAM

Unit	Major & Critical Failure Rate	95% Confidence Bands
Pulse Beacon	0.0044	0.00123 - 0.00985
Rate Beacon	0.0023	0.00028 - 0.00636
Decoder	0.0045	0.00122 - 0.00979
System	0.0112	0.0043 - 0.0182
System Mean-Time to Failure	89.0	

There exists no statistical significant difference between the rates shown in the table. From this we conclude that the verification program successfully simulated the field environment. The reliability statements that could be made about flights, assuming an exponential failure distribution, were stated earlier. In actual flights of Atlas Missiles guided by General Electric Mod III A/B equipment there have been no failures of the airborne equipment. This record is consistent with the results of the Reliability Verification Program. One of the six systems used "flew" 450 simulated flights without a failure.

Armed with knowledge of the validity of the Mod III A/B Reliability Verification Program, and faced with the task of evaluating the Mod III F/G guidance, range safety and tracking systems, we set about designing a program far more complex and more difficult to analyze statistically. For the Mod III F/G systems, the customer did not want to repeat a Verification Program. He wanted to know how reliable the systems were for various vibration levels. This information was needed to reflect the multipurpose use of the Mod III F/G equipments on more than one missile. Some of the levels envisioned with this new test program may even be beyond the vibration design specifications. The successful performance of the earlier Reliability Verification Program permitted General Electric to accept this challenge.

The new program differs from the Verification Program in a number of respects. Instead of simulating the flights of six systems at one vibration level, we are simulating the flights of the four systems at at least four different levels. A set of decision rules have been set down to determine the characteristics of the failure distribution. In this manner as soon as the failure distribution appears as recognizable, testing can be halted. By replacement of fatigued components and modules or both, testing can be resumed at another level.

The projected cost of the program seemed excessive at first; however, in reviewing the experience gained from the earlier verification program, the author decided that if time for countdowns were eliminated and flights were substituted, the number of flights could be more than tripled. By sacrificing the beauty of tight confidence bands, which are only obtained with large samples, a maximum liklihood estimate that was quite reliable could be obtained. Also, knowing some characteristics of vibration obtained from the Verification Program (discussed further on in this paper), the author felt he should be able to correlate the different vibration level effects on the equipment.

The Mod III F/G Vibration Evaluation Program is still in progress. One stage is complete. Four hundred successive failure-free flights have been simulated

at a vibration level comparable to those levels used in the Mod III A/B Program. This result is as good as, if not better than, what the Verification Program demonstrated.

Comparing the previbration experience of the Mod III F/G Vibration Evaluation Program with the data obtained from comparable field experience for the Mod III F/G equipment, one will find that the comparison is about the same as that for the Mod III B Reliability Verification Program (Table I). Such a performance pattern should be expected.

One additional comment is appropriate. The statistician knowingly sacrificed the beauty of tight confidence bands when planning the Mod III F/G Program. Originally he wanted about thirty failures for each system vibration so that he could estimate the failure-distribution function for each vibration level with a respectable confidence. This requirement was set aside by transferring the emphasis from a confidence level to a best estimate of the distribution mean. Generally speaking, the width of a probability confidence region is related to the size of the sample. The larger the sample, that is, the more flights observed; the tighter will be the confidence band. But this tightening of the confidence band will have very little effect on the estimation of the distribution parameters unless there exists a bias that is inversely related to the sample size. Thus, by deemphasizing confidence statement, and by concentrating on estimation of the maximum likelihood estimators of the distribution parameters, it is possible to reduce the sample size considerably. Table II illustrates this point.

TABLE II
Comparison of Failure-Free Flights Required at Two Levels of Reliability

R = 0.925		R = 0.985	
Lower Bound % Confidence	Failure-Free Flights Required	Lower Bound % Confidence	Failure-Free Flights Required
95	40	95	200
90	31	90	155
80	22	80	110
70	16	70	90
50	10	50	50

Second Lesson - Relation Between Time, Vibration, and Cycling

The debate between Production Environmental Testing (PET) exponents and dissenters has been going on for a number of years. PET, principally in terms of vibration, was debated at some length during the Sixth Military-Industry Missile Reliability Symposium at Fort Bliss in 1960. The simplest presentation of the issue of this controversy is, "Does vibration testing eliminate failures or does it cause them?"

One of the principal proponents for PET was Robert L. Stallard.* The rationale for PET is based on the fact that with compressed time schedules in complex missile systems, it becomes impossible to go through the ideal eight steps of production:

"1. Definition of the requirements.
"2. Production and test of the breadboard models.
"3. Production of a prototype, which is subjected to environmental tests.
"4. Redesign of the component, as dictated by the results of the prototype tests.
"5. Production of several prototypes with production tooling and production techniques.
"6. Full scale qualification testing of all these prototypes produced by production methods.
"7. Redesign and retest of the production prototypes, as necessary.
"8. Final production."

Essentially PET replaces the above steps with production hardware. Stallard stated the following levels (Table III) that his company used for PET tests.

TABLE III
PET Levels for Vibration Testing

Percent Components	Percent of Design Specifications
70	100
7	50 - 100
23	Below 50

Stallard does not feel that the PET programs shortens the life of the equipment. He has calculated that the maximum amount of design life consumed by PET for any component to be 4 percent.*

G. A. Henderson, in his paper, "The Fallacy of PET as a Quality Control Technique," presented at this symposium along with Stallard's, gave a well documented argument in opposition to the PET concept. He quoted extensively from Dr. W. R. Pabst's paper, "Statistical Planning for Ordnance Proof Testing." This paper

* Stallard, R. L., "The Value of P.E.T. As A Quality Control Function" Sixth Military-Industry Missile Reliability Symposium, Fort Bliss 1960, Volume I, Pages 303-324

argued that successful completion of a test run was in no way a guarantee that a torpedo would be more reliable. An experiment was devised utilizing two groups of five torpedos: Group A, which had passed a water run; and Group B which had not been water tested. Both groups were then water tested. The statistical analysis indicated that there was no significant difference between the two groups. In fact, the untested group empirically performed better, although the difference was not statistically significant. Such an experience is not unique. Similar results have been obtained from other programs.

Henderson, referring to a guided missile program utilizing 100 percent vibration testing said:

"... the contractor lists the following items as the kind of failures or defects he is finding: loose nuts and bolts; cold solder joints; insulation wearing through from rubbing, broken capacitor leads; capacitor shorting; microphonics on trimpots; microphonic transistors; intermittent relays; broken wires; broken mountings; cracked transistors; loose contacts; microsyn gear retainer failures; poor mechanical fit and looseness; defective pot wipers; snap-ring failures."

The contractor concluded that these defects "would not have been discovered during normal manufacturing inspection." He also made the "rediscovery" that "Manufacturing failures appeared to be completely random."

"I think we can assume safely," Henderson continued, "that if the contractor states that these failures and defects would not have been discovered during normal manufacturing inspection, either his normal inspection is no good, or else these defects were not present at the time of inspection, and were therefore, the direct result of the PET."

This writer was familiar with a missile program in which he demonstrated that the failure rate under vibration tests was the same as with tests not using vibration, and that this failure rate was essentially constant. The vibration testing as performed did not cause any increase or decrease in failures.

Over the years I have observed many failures such as unsoldered joints, broken welds in potted assemblies, that are supposedly vibration failures but that have been detected, not during vibration, but at some later time. The incidence of this type of failure, although not very high, is significant merely in the fact that it exists.

During the 1300 flights of the Mod III B Reliability Verification Program, four failures were observed. These failures were of klystrons, magnetrons, and thyratrons. These components have been considered by some as possessing a limited life. Cycling, time, vibration, or combination of these variables, could have been responsible for these failures.

Figure 3 shows a plot on Weibull probability paper of the four failures observed during the simulated flights. Notice how well the Weibull distribution fits the data in comparison with the exponential distribution. The Weibull distribution indicates that time, cycles, or vibration did affect the life of the system.

It is interesting to compare the earlier statement made about the reliability of the Mod III B equipment with the statement that would be made with this best estimate of a Weibull fit.

1. Assuming an exponential distribution: With 95 percent confidence, equipment reliability for a countdown and flight period is no less than 0.994.
2. Assuming the Weibull distribution: With 95 percent confidence, equipment reliability for a countdown and flight period is no less than 0.999.

The second statement implies that repeated cycling, time, or vibration does have an effect on reliability. The reliability on a single flight would be higher under a Weibull assumption than under the exponential assumption. Figure 4 shows the relationship of the cumulative conditional distribution functions of the two distributions. This shows the expected number of failures that one would observe from time zero to time t.

The Mod III B Verification Program was not designed to separate the effects of vibration, cycles, and time. Upon completion of the flight portion of this program, a life test was partially performed on two systems. The equipment was subjected to few on/off cycles and to no vibration. The result of this incompleted test indicated that with steady operation the equipments operated for 3600 hours with a MTBF of 350 hours as opposed to 100 hours for the flight period.

These results still do not reveal the relation between time, vibration, and cycling. We have to look to our Mod III F/G Vibration Evaluation Program and to an additional experiment. The Vibration Evaluation Program as it stands today is inconclusive. It would appear that vibration levels do have an effect. One system completed 400 cycles at low-level vibration without a failure. Another system, at a level three times as high, had a failure after 92 cycles. The evaluation program, however, is designed so that upon completion we should be able to give a better answer to the question of the effect of vibration.

The other important experiment is the life test that we have been performing on the Mod III F/G klystrons. In this test,

the klystrons are cycled once every hour of the day in a manner that simulates the normal test for the beacon. Each cycle reproduces the temperature and signal pattern that would be observed during a normal beacon test. The results of the test to date are shown in Table IV. The principal difference between the two klystrons is the power mode. The MISTRAM klystron should have a longer life than the Mod III F/G klystron.

TABLE IV
Klystron Life-Test Results

		hours	
Mod III F/G Klystron	1	1300	failed
	2	1453	failed
	3	1613	
	4	1602*	
MISTRAM Klystron	1	1876	
	2	1876	
	3	1876	
	4	1870	

The life expectancy of the klystron is quite a bit more than had been expected. It was generally believed that a klystron after one hundred hours was a reliability risk. Very little change in the operating characteristics of the klystron has been observed during this life test. Although these klystrons are not the same as those of the Mod III B, they are comparable to the units used in the Mod III F/G Vibration Evaluation. If the performance under vibration is not the same as the static performance, the influence of the vibration environment on life will have been demonstrated more definitely than in the past.

An interesting observation about the two failed klystrons is that both show a general over-all deterioration of the cathode. Those that have failed in the field because of deterioration of the cathode, which would be considered normal end of life, have deteriorated only in a localized spot near the center.

The results of the Mod III B Reliability Verification Program, the Mod III F/G Vibration Evaluation Program, and the Klystron Life Test to date tend to support the thesis that vibration does have an effect on the life of electronic equipment. The next question to ask is, "How much?" The Verification Program was performed at operational flight vibration levels. Vibration testing at these levels, within reason, may have only a minor effect on the life of the equipment.

When completed, the Mod III F/G Vibration Evaluation Program will tell us more about the influence of vibration levels on the life of the airborne equipment.

At this point it can be said that repeated vibration at high levels will affect the reliability of a system. Thus, if a system was vibrated, failed and then vibrated again at a high level, its reliability could be affected adversely by fatigue. One way to avoid such fatigue would be by designing the equipment with a greater safety margin. Another method to avoid fatigue would be to shorten the vibration-test time. A vibration expert told this writer that a one-minute random vibration is all that is required to excite all possible resonances in the frequency spectrum under test. All vibration beyond that point only fatigues the unit.

The Mod III B Reliability Verification Program has indicated that vibration at the simulated flight levels had a slight effect on the life of the equipment. Vibration at some higher level would probably have introduced more fatigue. This has been apparent with the Mod III F/G Vibration Evaluation Program.

This writer's personal position in the controversy surrounding PET is that it is not a panacea for detecting loose bolts and nuts, cold solder joints, and so on. After vibration tests, these defects do appear. If the vibration test is not effective, one would expect to observe these failures with about the same frequency as before. If the test is effective these failures should not exist. This presupposes that the failures are not due to fatigue but that marginal conditions are being detected. What is required then is an effective short vibration test. The problem usually is that the length of a vibration test is determined by the time required for electrical performance test, and not by the requirements for an effective vibration test. If the vibration-test time is not determined by electrical-test time, it is usually determined by custom; actual requirements are not taken into account, or more seriously, are not even known.

If we approached our designs with the same conservative safety approach as a bridge designer, we would not have to be concerned as much with the degrading effect of vibration. It is unfortunate that in our missile-space age definite tradeoffs of size and weight, and thus safety, must be made.

Strictly speaking, I would like to be completely on Henderson's side because I feel that PET is being used to detect our human failings and carelessness. I also feel that time spent on proper evaluations of design and manufacturing processes would be more effective in producing reliable equipment than time spent on PET inspections. The answer is not PET or no PET. It is the rational development

* Retune klystron after 35 hours.

of design, manufacture, and test equipment. If we are to use PET to detect our human failings, we are not treating the cause of our illness. Fundamentally, workers want to do a good job and take pride in their work. But if they work from chaos and panic, change one thing after another because of our engineers' errors, are rushed by foremen so that they meet schedules, their morale, and with it the quality of their product, will slip. If our designers must rush a design into production because of contract requirements, the design will soon have to be changed and the chain reaction leading to poor quality will be started.

The Little Prince upon visiting the earth and our cities wisely observed: "Men set out on their way in express trains, but they do not know what they are looking for. Then they rush about, and get excited, and turn round and round..." (Antoine deSaint Exupery, The Little Prince, Reynal and Hitchcock, New York)

Perhaps our chain events are described by the meeting of the Little Prince and the tippler.

"What are you doing there?", He said
"I am drinking" replied the tippler
"Why are you drinking?"
"So that I may forget."
"Forget what?"
"Forget that I am ashamed."
"Ashamed of what?"
"Ashamed of drinking."

Third Lesson: Time

The Mod III B Reliability Verification Program was useful because:

1. It attained its objective: verification of the reliability of the Mod III A/B airborne system.
2. It yielded valuable information on the distribution of failure.
3. It pointed out design and component weaknesses, either independently or in conjunction with the field experience of the Mod III A/B equipment.
4. It gave us an engineering "confidence" in the validity of our testing procedures. Not only with the procedures of the test program, but more important, with those used for production and for field testing. The test-program results were also instrumental in making two changes in the manufacturing and inspection procedures.
5. It facilitated a rapid formulation of new evaluation methods utilizing the knowledge attained.

But all of this is not enough. The timing and time scale of the program was such that a major part of its potential value was lost. There is a need to have known yesterday what we hope to learn tomorrow. The time to perform such a program is often too great. The time to negotiate such a program is often too great. The time to analyze the results and make the answers known is often too great.

Time is involved because evaluation programs cost money. This writer as a statistician who has taken an active part in planning many evaluation programs is well aware of the time problem. He is aware of the necessity of having a meeting of the minds so that there is a complete understanding among all parties. Each program that I have been involved in proved valuable. But in each case time has detracted from the value of the outcome.

There is too much that is unknown in our industry today to permit our running around without a purposeful plan. Each new evaluation must not be just a repeat of something that has been done before, but one that is designed to yield new information in an orderly fashion. It is essential that each plan be carefully laid and utilize all the knowledge available.

It would be convenient if we could organize one grand and glorious program to tell us all. This is not possible. We must think instead of an over-all concept, and fit into this concept test programs as parts of the fulfillment of that concept. The problem of PET or nonPET is not what we need to resolve. We need to know that we have developed the criteria required to assure that we have a reliable product. This problem doesn't involve only testing. It involves manufacturing. It involves design.

> "...Failure data indicates that the principal reasons for failure are human. The largest single source of unreliability is workmanship. The second largest source is design and manufacturing engineering. These two sources combined are responsible for 70 percent to 90 percent of the failures reported. Both sources could be called workmanship. The first is workmanship of the hand and the mind. The second is workmanship of the mind and the hand. They both exist because of the attitudes of human beings."*

The proponents of PET are, in effect, admitting that they require such techniques because they have poor assurance of the manufacturing and design.

The opponents of PET insist that, "Contractors determine appropriate environmental conditions, test to failure adequate samples of R&D (and later production) hardware in these environments, and demonstrate the existence of adequate safety margins."**

*Christian, D.B., "Human Attitudes and Reliability," 1959 Northeast Electronics Research and Engineering Meeting

**Henderson, George A., "The Fallacy of PET As a Quality Control Technique," Sixth Joint Military-Industry Guided Missile Reliability Symposium, 1960

This writer is of the opinion that the evaluation must be performed early in the program. In the words of Alexander Mood, "The heart of a reliability program for a complex mechanism is early detection of design weaknesses by the performance and analysis of environmental test experiments on prototype or pilot models of major parts of the mechanism. Such a program must be carried out jointly by design engineers, experts in environmental testing and statisticians thoroughly versed in the practice of experimental design; it must be completed before the onset of the scheduled production."*

It has been shown over and over that the problems observed in most evaluation programs are the same ones observed during production. Three years ago I said, "If design and environmental testing are not performed in the early prototype phase of a program, the design problems will confront production personnel throughout the program. Temporary fixes or living with the problems will not solve them. We cannot close our eyes and hope for design faults to silently fade away."**

Time appears as the critical parameter because of the acceleration of our complex missile programs. I am familiar with one program in which statistical evaluation was utilized in the design phase. This evaluation did pay off.

Time has been used in that we have, in the Mod III F/G Vibration Evaluation Program, made use of what was learned from the Verification Program. But to be more effective we must reduce the time delays. The planners must be completely aware, not only of what their objectives are, but of what has been done in the field and of what the major questions that exist are. And they must plan so that we can get closer to the answers. It is then their responsibility to make known their results whether success or failure.

Every system-evaluation program that I have been related to or have observed has shown definite characteristics. The failures that exist are similar to the ones that will or have plagued you in production. They all stem from the same behavior pattern. It is essential to determine this pattern in a new equipment program as early as possible. What Mood said above is true. If we are to get off our merry-go-round, our evaluations must exist and must start as soon as possible. Their scope must be determined, not by custom, blindness, or naive planning, but by intelligence, ingenuity, and daring.

---

* Northeast Electronics Research and Engineering Meeting, (Mood see footnote as quoted by D. B. Christian)

** Ibid

1773

THE SUCCESSFUL APPLICATION OF A REPEATED TEST-TO-FAILURE PROGRAM ON SERGEANT MISSILE ASSEMBLIES

The purpose of this paper is to present the Sperry Utah Company test philosophy and the results of a reliability test program, which led to the achievement of many of the reliability goals of the Sergeant System.

The tests discussed are the results of the practical application of a test-to-failure program based upon Latin square and regression analysis models. The statistical theory was presented in a Sperry Utah paper by Dave White at the Sixth Joint Military-Industry Guided Missile Reliability Symposium at El Paso in 1960.[1]

Early in the R & D program the reliability efforts were directed primarily to component evaluation. As the R & D program progressed and production hardware became available the emphasis was placed on assembly and subassembly evaluation. This test program was designed and put into effect to assess the capabilities of the Engineering Model to meet its expected environment, including allowance for variations in environmental extremes. The program included reliability tests as well as type approval environmental tests. The Sperry Utah approach to reliability testing utilizes a repeated test-to-failure model to verify quantitatively the ability to the system to satisfy the number one military characteristic, reliability. The type approval tests determine assembly design limitations.

The test program is discussed in three parts, Part I discusses the testing aspects whereas Part II discusses the mathematical analysis aspects, and Part III discusses the conclusion and recommendation.

PART I. THE DESIGN, APPLICATION, AND RESULTS OF THE COMBINED OPERATING TEMPERATURE & VIBRATION TEST FOR MISSILE ASSEMBLIES RELIABILITY

Richard H. Brashear Jr., Principal Engineer
Sperry Utah Company
Salt Lake City, Utah

Test Philosophy

Sperry Utah's reliability test program incorporates repeated tests-to-failure in addition to the type-approval tests. Sperry Utah defines type-approval tests as being environmental tests to a specified level whereas reliability tests extend to several environmental levels and involve sample sizes large enough to ensure statistical confidence. Type approval tests are conducted for non-cumulative types of environments with respect to reliability degradation. Non-cumulative environments are defined as those which occur in the normal course of use and which can be offset by proper design, i.e., transportation and operation altitude, sand and dust, salt spray, rain, storage, temperature, humidity, fungus, and static acceleration. Repeated tests-to failure are conducted for environments considered to be cumulative, i.e., those attendant on normal use and which result in wearout or aging of the equipment. Examples of cumulative environments are transportation vibrations, shock due to bench handling and drops, hot and cold operating temperature, and operating vibration.

Test Program

The repeated test-to-failure program was designed to facilitiate from a minimum sample size a statistical analysis of mean-life data to produce such flight reliability parameters as 90-percent confidence limits, maximum safe operating level (MSOL), and average strength. Consequently, a simulated flight environment consisting of ambient temperature and random vibration was imposed concurrently upon each of three test samples. Each missile assembly type was tested at three different vibration levels and in three mutually perpendicular vibration planes.

The general plan was to test each of the three test assemblies until six failures were observed on each assembly (a total of two failures per test level) or until each assembly was subjected to 90 minutes of vibration. (10 minutes per plane for each of three discrete vibration levels). The sequence of planes, stress levels, and test environments is discussed below.

Table I-1 shows a typical Latin square design used with each type of assembly. The three vibration tape levels, V_1, V_2, and V_3, are applied to the three assemblies in the order indicated in the table. During the test, the assemblies are operating and their performances are monitored. If a failure occurs, a repair is effected and the test resumed. In practice, three test patterns occurred: two failures; one failure and survival to the time limit; and no failure and survival to the time limit. The XYZ notation under V_1 denotes the vibration plane (corresponding to the missile roll, yaw, and

pitch axes) ordering for the application of vibration. For example, assembly No. 1 at the V_1 level was vibrated for 10 minutes in the X plane, 10 minutes in the Y plane, and 10 minutes in the Z plane, provided no failures occurred.

Table I-1
Latin Square Test Design

Assembly No.	Vibration Level			Temperature
1	V_1 XYZ	V_2 YZX	V_3 ZXY	T_1
2	V_2 ZXY	V_3 XYZ	V_1 YZX	T_1
3	V_3 YZX	V_1 ZXY	V_2 XYZ	T_1

The procedure for assemblies Nos. 2 and 3 is essentially the same except that the order of vibration differs. The test levels are proportional to the flight levels specified for each missile assembly.

Program limitations for the Sergeant dictated testing at one temperature level only, T_1, therefore, the temperature level selected was biased high to ensure a conservative reliability estimate.

One advantage of the Latin square design selected is that wearout effects in the equipment can be isolated. Significantly, the test results indicated that equipment wearout was negligible for Sergeant missile assemblies.

Test Environment

The selection of critical temperature and vibration test levels was based on a study of the prescribed Military Characteristics (MC's), field operation tests, and an analysis of R & D missile firings of the Sergeant. This evaluation showed that the critical missile temperature environment resulted from desert conditions encountered during checkout and countdown. Consequently, during an actual flight missile cooling rather than heating occurred.

The assembly ambient temperature was determined from controlled environmental tests made on the Sergeant at Jet Propulsion Laboratory and at Sperry Utah. During the tests the missile was subjected to the high temperature MC requirement of 125°F ambient plus solar radiation of 360 BTU/ft^2/hr for 4 hours a day with the assemblies instrumented for recording temperatures.

Table I-2 shows the temperatures both recorded and selected for the reliability test.

Table I-2

Missile Assembly	Ambient Temperature From Tests (°F)	Reliability Test Temperature
Guidance Platform	137	145
Control Assembly	131	140
Guidance Computer	134	145
Arming Computer	130	140
Arming Platform	130	140
Frequency Regulator	151	160
Motor-Generator	156	165
Control Surface Actuator	180	180
Antenna Assembly	180	180
Interconnecting Box	180	180
Cable Assembly	180	180

The most severe actual vibration environment of the missile in flight results from the dragbrakes being extended into the air stream. For some assemblies this vibration is quite severe. Formerly, the mean extreme vibration environment of the missile was defined by the random vibration (noise) as measured at the Standard location (a monitoring point located on the primary structure at the root of the dragbrake). However, each missile assembly experiences different vibration inputs during flight caused by differences in mounting and local resonance of the guidance section structure. Thus it was apparent that use of a standard tape was imposing unnecessary design restrictions on some assemblies as well as biasing reliability estimates too conservatively. As a result, Sperry Utah instituted a program to determine the in-flight vibration environment of the guidance assemblies and synthesize a realistic test for each assembly.

Because the test philosophy[1] dictated a constant rms vibration level all pertinent vibration parameters, i.e. bandwidth, peak level, and rms level were easily controlled. Random noise with the desired power-spectral-density shape was recorded on magnetic tape which was then used to provide input excitation for the test. The desired vibration level was maintained at the shaker by a gain control in the shaker control console. Thus, vibration level was independent of the noise level recorded on the test tape.

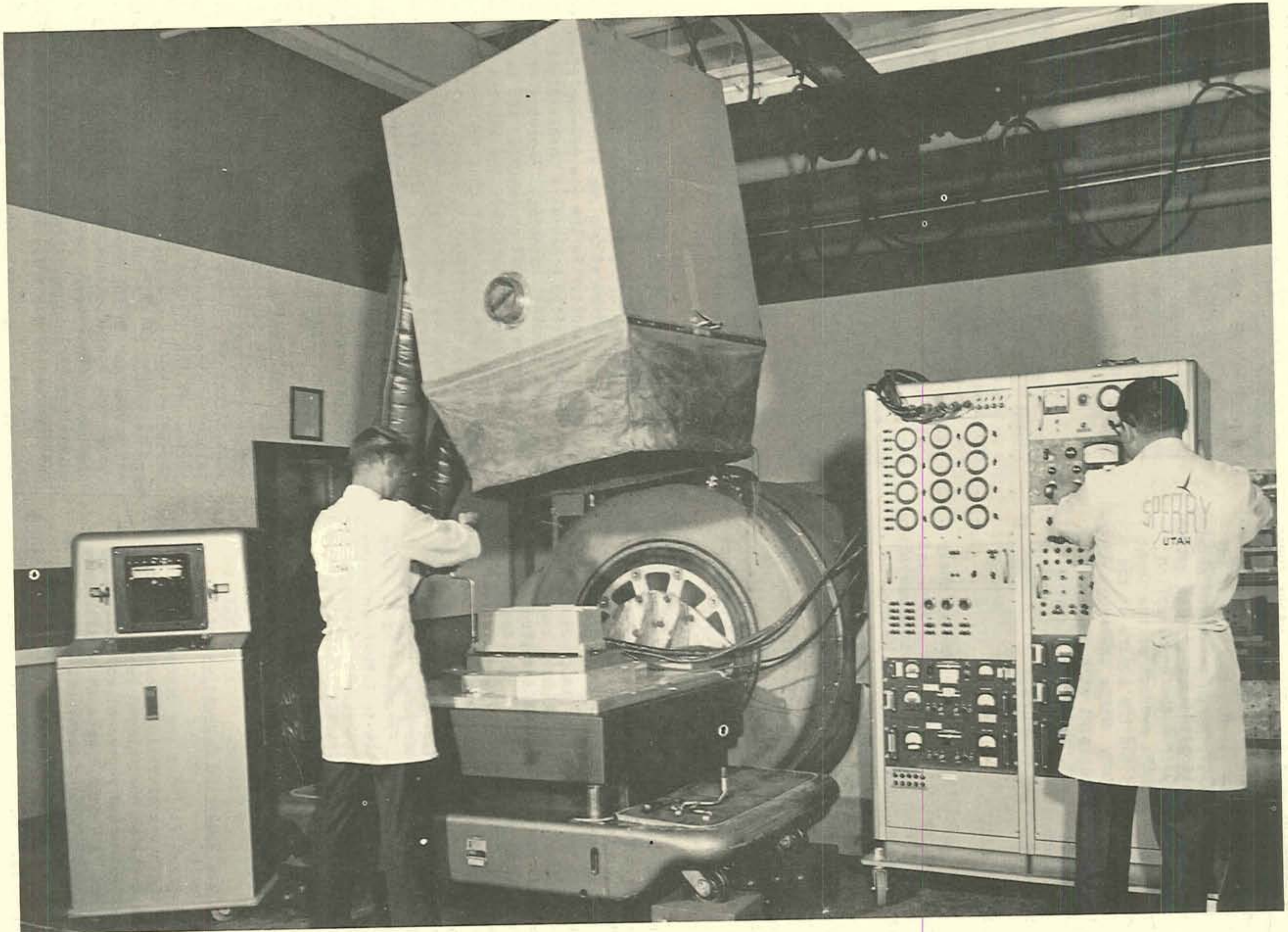


FIGURE I-1. COMBINED ENVIRONMENT TESTING OF MISSILE ASSEMBLIES

The noise was shaped by passing "white" noise through the peak-notch equalizing circuitry in the shaker control console. The transfer function of the circuitry was adjusted until the output power-spectral-density shape agreed with measured in-flight vibration. (In Part II of this paper, several figures are presented showing plots of flight vibration and time.) The output power-spectral-density from the equalization circuitry is equal to the product of the input power-spectral-density and the square of the system transfer function. Since the input power-spectral-density was constant with respect to frequency (white noise), the shape of the output power-spectral-density was proportional to the square of the transfer function.

Effecting the Test

All test assemblies were mounted in their appropriate shaker table adapting fixtures and then given an 8 hour pre-soak at test temperature. The test equipment consisted of an MB Mfg. Co. C-200 vibration exciter (20,000 lb rms force class) used in conjunction with a 90 kilowatt power amplifier and control console capable of generating the random voltages required. Two planes of shake (Y and Z) also required the use of a Wylie Model WM-450 oil film table. Temperatures were maintained by a Wylie Model TC-109C temperature controller used in conjunction with a Sperry Utah built portable temperature hood. Before the test was set up, an oil film table was pre-heated under a temperature hood for 30 to 45 minutes. When the temperature soak was completed, the test assembly and fixture were removed from the temperature chamber and mounted on the oil film table in as short a time as possible (2 to 3 min). The temperature hood with the specimen inside was mounted again on the oil film table and the required cabeling and test accelerometers were connected to the assembly. See figure I-1. To eliminate fixture effects, the test accelerometers were mounted on the test specimen rather than on the fixture. The system acceleration voltage transfer function between the specimen and the exciter power supply was equalized over the desired frequency band. This process took from 20 minutes to 1 hour and allowed enough time for the test assembly to reach temperature equilibrium before the shake test began. After equalization, the test specimens were subjected to random vibration levels, as specified in the Latin square process, for the prescribed times or until a failure was indicated.

Typical Failure Modes and Corrective Action

Four typical failures are discussed to illustrate the types of failure modes and areas of corrective action encountered in the tests. The failures discussed represent an engineering design failure, a vendor component quality control deficiency, a vendor component design deficiency, and a workmanship defect.

Frequency Regulator (Engineering design failure). Of greatest importance was the repeated failure of two identical capacitors in the motor-field drive subassembly of the frequency regulator. The capacitors are 60 mfd, 30 volt tantalum capacitors. This component alone accounted for five assembly failures and ten component failures. The principle modes of failure were either fracturing of the tantalum lead between the tantalum slug and the seal washer or a seal breakage resulting in the loss of electrolyte. See figures I-2 and I-3.

One of the main causes of this failure was the packaging design. It was shown that the resonant frequency and the subsequent excitation amplification at the failure location occurred at the same frequency, see figure I-4. Consequently the capacitors were subjected to a severely increased vibration environment. It is possible that with 15 g rms of vibration excitation, capacitor environment was in excess of 58 g rms over the frequency spectrum with instantaneous peaks of 200 g occurring infrequently. Because these stress levels exceed the failing component's environmental specification a design modification was required.

Sperry Utah redesigned the circuit board to reduce the total resonance condition and suggested further component redesign changes to the vendor.

Guidance Platform (Vendor component quality control deficiency). A different mode of failure occurred after 20 seconds of operation of a guidance platform at 5 g rms vibration. A 1 mfd teflon capacitor in the yaw pre-amplifier integrator had failed because of insufficient dielectric terminal wrapping. Analysis of the component revealed that an inserted tab lead had pierced the teflon dielectric and shorted one winding. It was also found that the two 0.5 mfd windings were insufficiently restrained in the "bathtub" case by teflon waste thus allowing excessive lateral movement. The failure mode was classed as vendor quality control defect since considerable effort was expended with the vendor early in the program to effect a capacitor design consistent with Sergeant environmental requirements. See figures I-5 and I-6.

Control Surface Actuator (Vendor component design). The Sergeant's control surface actuator assembly was vibrated in the X plane at 20 g rms. After 36 seconds of vibration a 10 kilohm telemetry potentiometer wiper intermittently lifted off the pot and caused a noisy output. An investigation showed that the wiper support slipped laterally on the control shaft. The support was positioned on the shaft by bonding. The vendor has since improved the potentiometer design by adding spacers between the three wiper assemblies to preclude slippage of the wipers. See figures I-7 and I-8. Since this failure

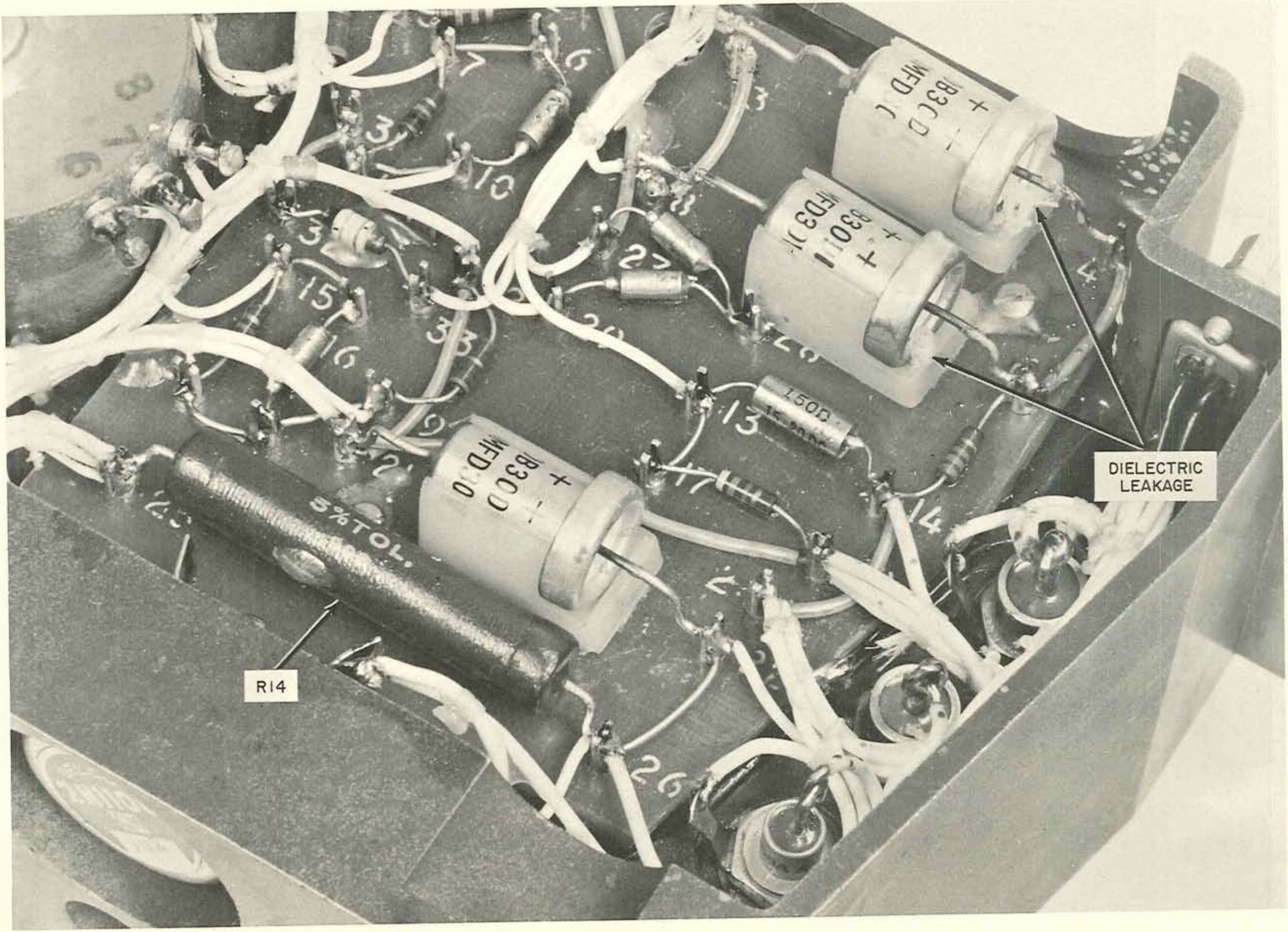


FIGURE I-2. FREQUENCY REGULATOR SUBASSEMBLY SHOWING CAPACITORS WHICH FAILED IN VIBRATION

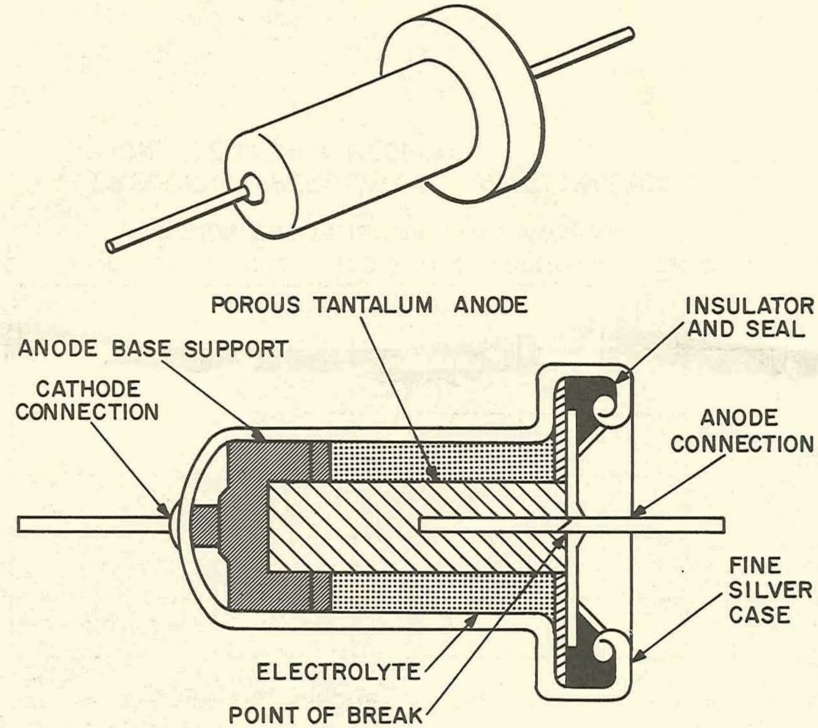


FIGURE I-3. FAILED TANTALUM CAPACITOR, CROSS SECTION

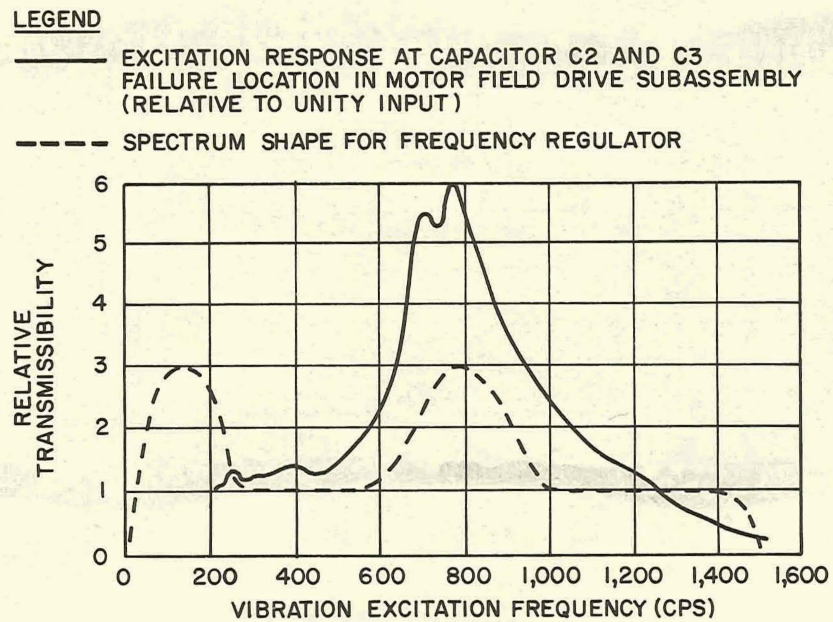


FIGURE I-4. FREQUENCY REGULATOR VIBRATION EXCITATION FREQUENCY RESPONSE

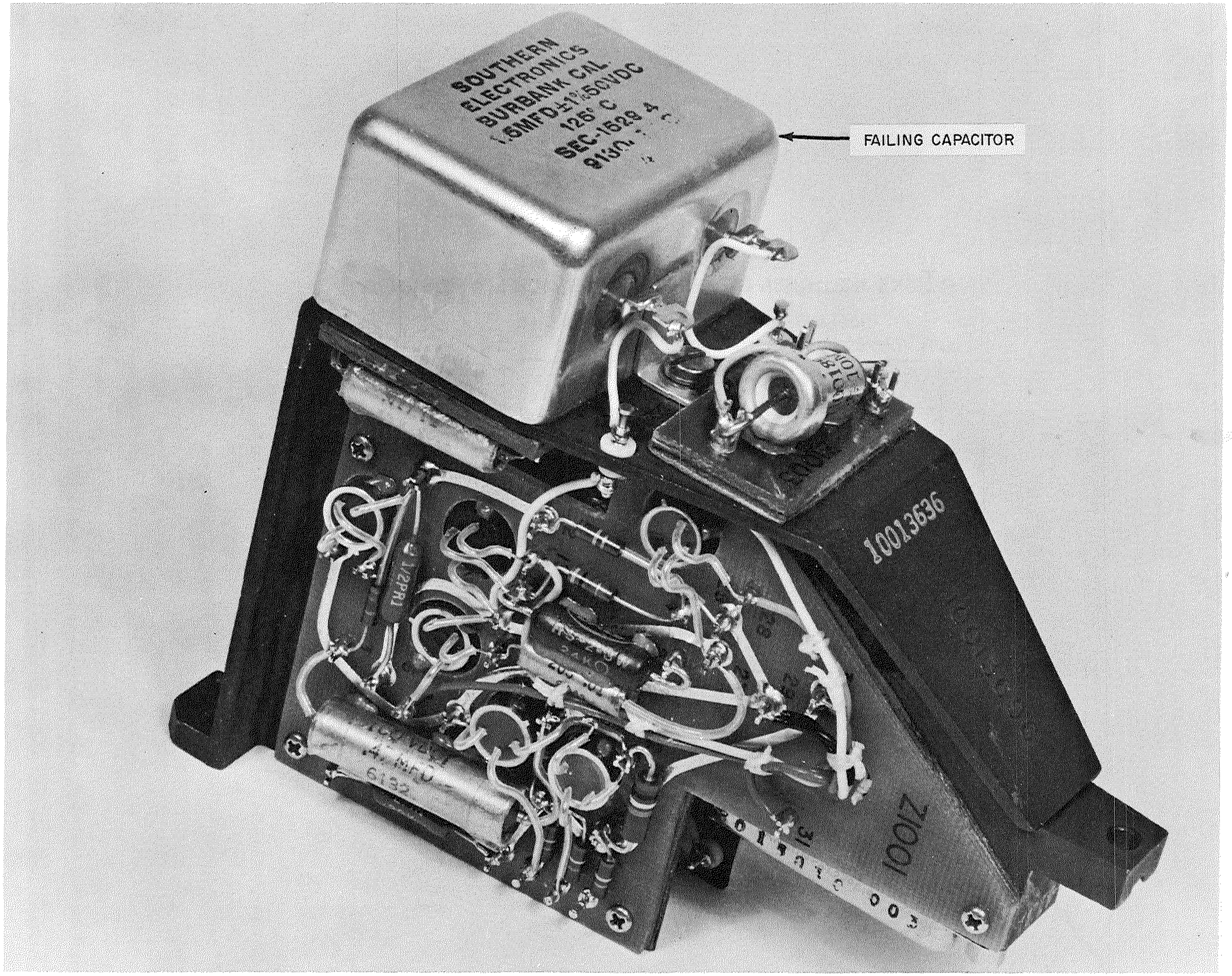


FIGURE I-5. GUIDANCE PLATFORM SUBASSEMBLY SHOWING CAPACITOR WHICH FAILED IN VIBRATION

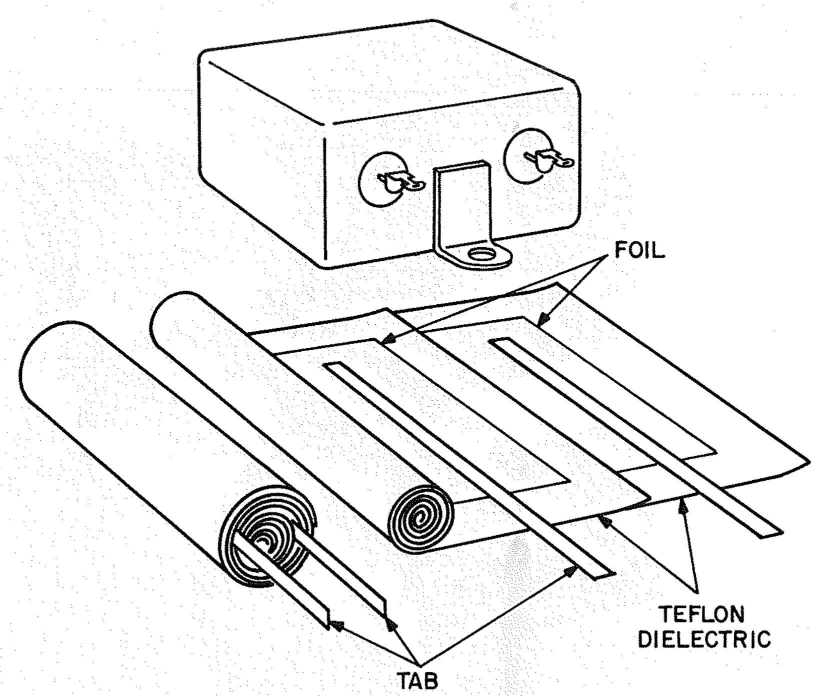


FIGURE I-6. FAILED TEFLON CAPACITOR, CROSS SECTION

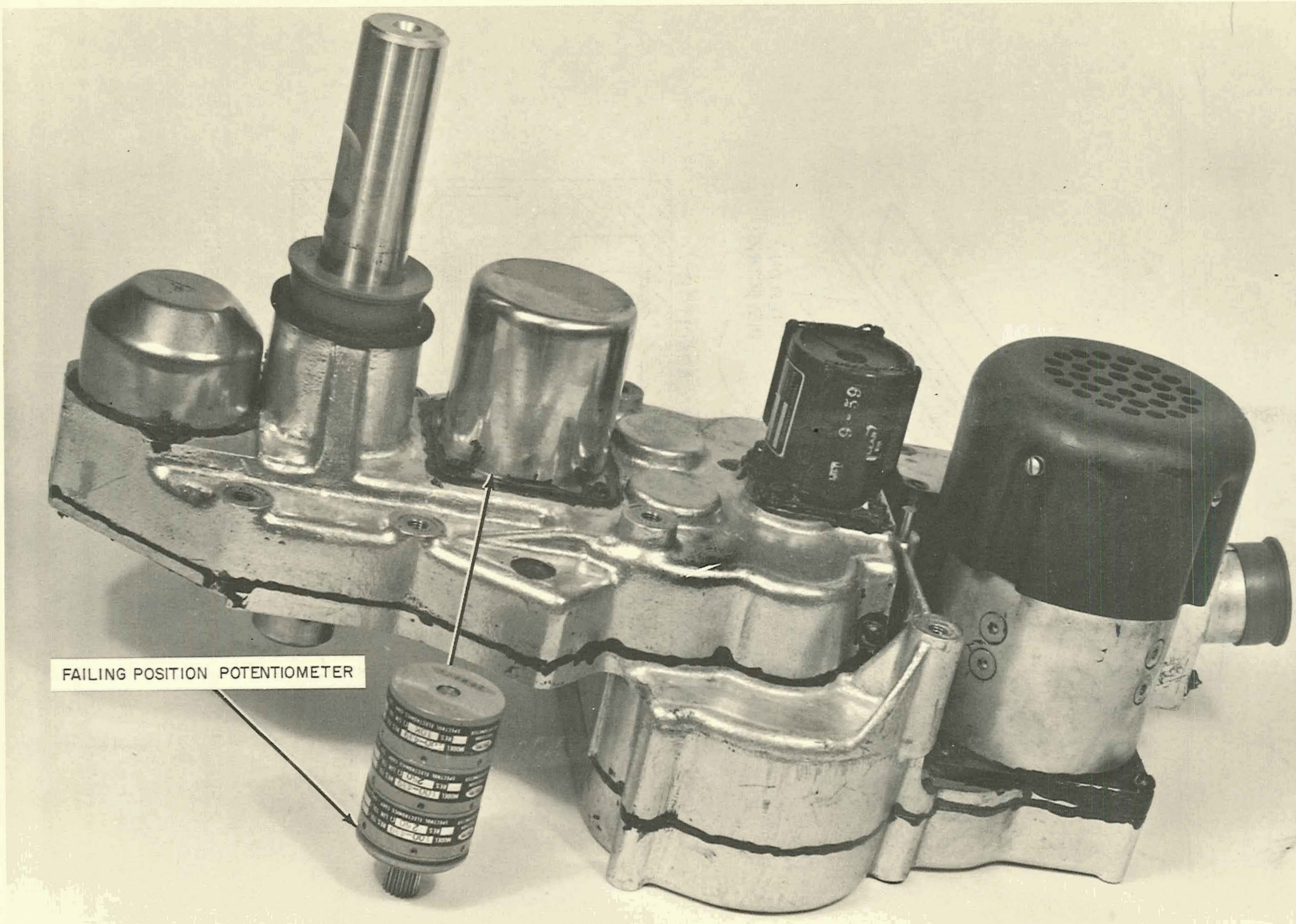


FIGURE I–7. MISSILE FLAP ACTUATOR SHOWING POSITION POTENTIOMETER WHICH FAILED IN VIBRATION

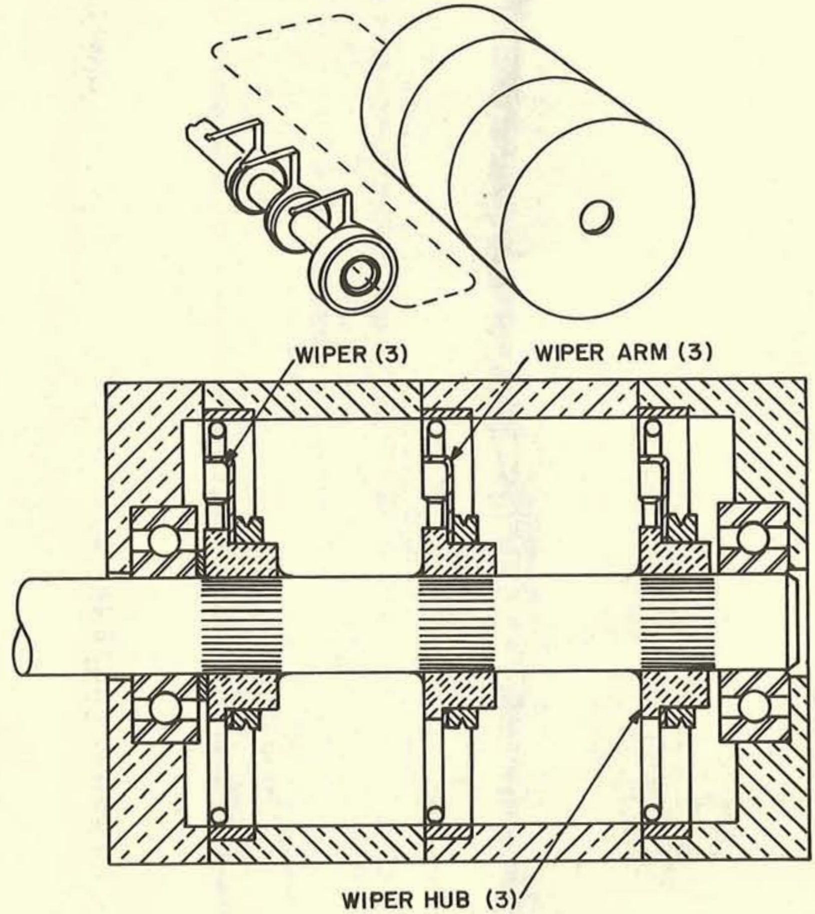


FIGURE I-8. GANG-POTENTIOMETER, CROSS SECTION

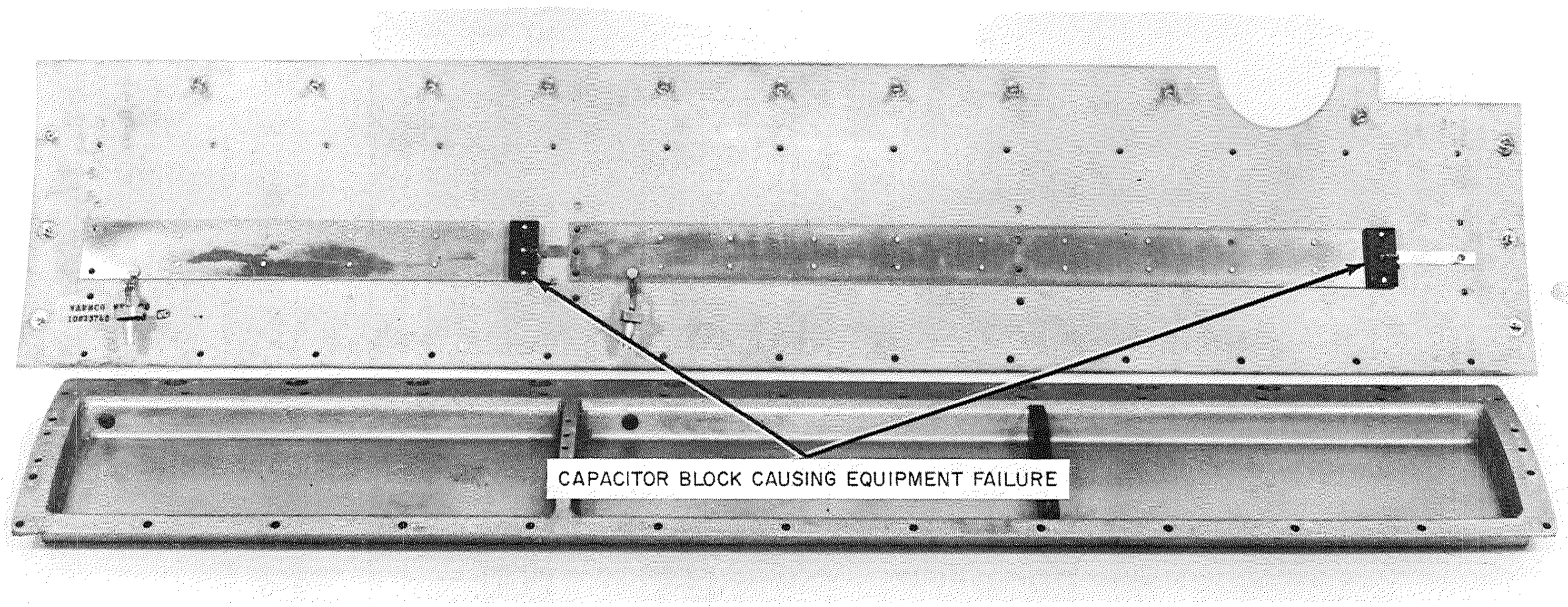


FIGURE I-9. NORTH—EAST QUADRANT ANTENNA SHOWING CAPACITOR BLOCK ASSEMBLY WHICH FAILED IN VIBRATION

occurred on a non-tactical component the failure was not considered pertinent in the statistical evaluation of the reliability indice for this assembly.

NE Quadrant Antenna Assembly (Workmanship error). The northeast quadrant antenna assembly of the missile consists of two DOVAP antennas. The receiving antenna (36.9 mc) detects ground-transmitted signals which are then amplified, doubled in frequency, and retransmitted to the ground by means of the transmitting antenna (73.8 mc). The function of the DOVAP is to aid in establishing velocity and position information of the missile during flight. Two of the three NE quadrant antenna assemblies failed because the 36.9 mc and 73.8 mc terminating capacitors were short-circuited in their mounting block assembly. See figures I-9 and I-10.

These failures occurred because poor installation forced one of the capacitor leads to short against the capacitor case. The corrective action taken was to instruct the assembly personnel in the proper assembly techniques and to inscribe caution notes on drawings and operation sheets. Most of the failure modes encountered as a result of the combined operating temperature vibration environment were failure modes that had not been observed on earlier type-approval and flight acceptance tests.

Test Problems

Four problems are discussed to illustrate the type of test problems encountered in effecting the program for the first time.

Equipment Operating Mode. The Sergeant missile is designed for maximum flight time of approximately 200 seconds. During this time, the guidance computer, an analog computer, performs the following functions:

(1) Computes missile deviations from the programmed trajectory during the initial period of flight and provides correction signals to maintain the missile on the correct trajectory.

(2) Computes missile deviations from the standard range position during the flight and provides signals for drag-brake closure commands for vernier range control, and the final phase maneuver.

(3) Provides a warhead arming permit command when the missile is within prescribed range and azimuth bounds.

To test the guidance computer functionally, a standard trajectory is simulated by test equipment but the standard flight time is compressed to a 90 second period. During this simulated flight, functional parameters such as integration and cross-over time are monitored and compared against the standard performance times. The test philosophy dictates 30 minutes of vibration per test level if no failures occur. To utilize existing test equipment the assembly was subjected to repeated simulated flights of 90 seconds. The computer was rezeroed and the parameters were reinserted between flights, until a failure occurred or the testing time was completed. The control assembly tests were conducted in a similar manner. Satisfactory test results were obtained but the test setup time was excessive.

Determination of Failures. The determination of catastrophic failures during the flight mode was not difficult but the determination of non-catastrophic failures in some cases presented problems. For example, the Bell Accelerometer utilized in the Sergeant guidance platform is designed with a noise threshold limitiation of approximately 15 g. When this noise threshold was reached, usually within one second of vibration at 15 g, the accelerometer outputs which were monitored as a pertinent performance parameter saturated. The initial reaction from test personnel was that a platform failure had occurred. Although the problem was basically simple, a certain amount of analysis and discussion was required within the Engineering groups to validate the classification of the failure and its treatment during the rest of the tests. The treatment was to ignore the accelerometer performance at the higher vibration level test. It is interesting to note that Sergeant guidance platform performance at the higher vibration levels exceeded expectations. This performance led Engineering to conclude that after quality control type defects, (i.e., the capacitor construction failure previously discussed) have been resolved the guidance platform is quite reliable relative to its complexity.

No-Failure Problem. The test philosophy was based on the assumption that failures would occur during tests. Prior to testing Engineering did not assume that any missile assemblies would show no failures. This "failure will occur" view was held not because of pessimism or lack of confidence in the equipment design but rather from the consideration that the temperature-vibration environment over the limit was extreme. Because some missile assemblies did not fail during the tests a different statistical model had to be developed to replace the Latin Square repeated test-to-failure philosophy to preclude biasing the reliability indices too conservatively. The extension of this statistical theory is discussed in Part II of this paper.

Operations Problems. In evaluating the test program itself, major difficulties were apparent in obtaining and maintaining the test equipment, equalizing the vibration system for the parituclar noise tapes, and changing equipment to conform with the randomization pattern for test specimens and vibration planes imposed by the Latin Square design. However the tests were facitilated

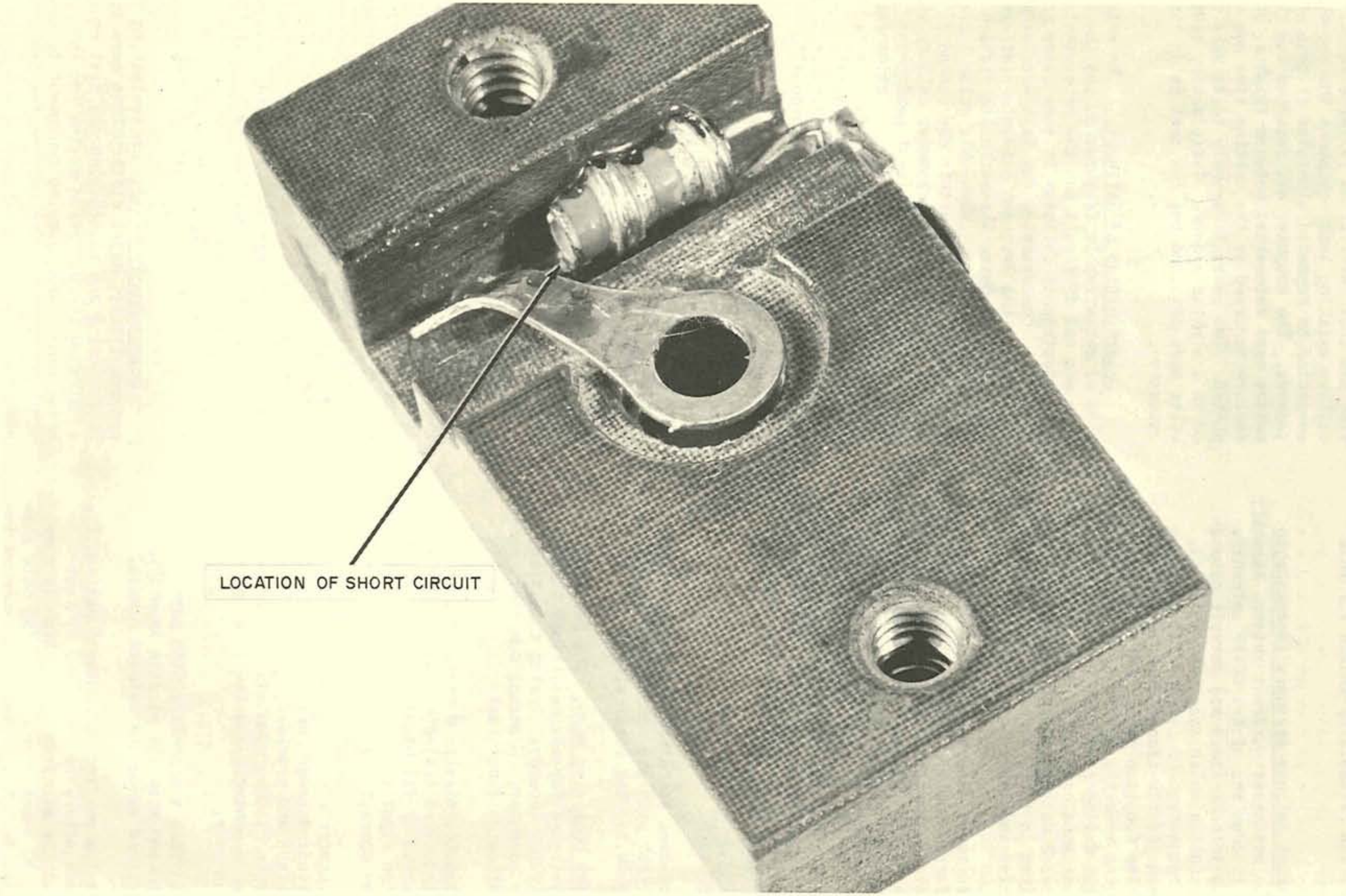


FIGURE I-10. CAPACITOR BLOCK ASSEMBLY, MANUFACTURING DEFECT

through scheduling environmental tests only when three working assemblies of each type were available and utilizing the pre-soak temperature chamber to condition the assemblies. The institution of the pre-soak chamber effected a considerable reduction in environmental test time and the number of shaker plane changes. It was generally concluded that the test and vibration equipment itself had more reliability limitations than did the Sergeant hardware under test.

In a test program of this magnitude, providing an adequate supply of spare parts for failed assemblies in a time frame consistent with the schedule requirements constitutes a significant problem. Sperry Utah attempted to resolve this difficulty by predicting in advance failure modes, using production parts for repairs and by restocking parts as they were used. Typically, many predicted failures did not occur while many non-predicted minor component failures did occur thus causing repair part procurement problems. The author has no particular recommendation for improvement here as replacement parts coverage for a reliability test program should be evaluated with respect to overall program cost and schedule limitations.

PART II. STATISTICAL TECHNIQUES APPLIED TO THE SERGEANT REPEATED TEST-TO-FAILURE PROGRAM

Larry Blundell, Research Engineer
Sperry Utah Company
Salt Lake City, Utah

Latin Square

The design of the reliability test program and the analysis is based upon the following statistical model. Three units were tested at each of three different vibration stress levels for a period of 30 minutes unless a failure occurred prior to 30 minutes. If a failure occurred, the faulty unit was repaired and retested for another 30 minutes under the same qualification. If no failure occurred during the second 30-minute test period, a conservative estimate of time to failure was assumed to be 30 minutes.

The order in which the stress levels, (g) were applied to the items is shown in the 3 x 3 Latin Square in tables II-1, 2, and 3. An estimate for the mean life, which is different for each stress level at which the unit is tested, is

$$Q^K_{JLQ} = \frac{T^K_{JQ} - T^K_{JQ-1}}{2} \qquad (1)$$

where

L = stress level

T^K_{JQ} = total time for which the Jth unit has been stressed at the Qth stress level applied, and at all previous stress levels

K = positive integer

Estimates for the mean life are shown in minutes in the Latin square in tables II-1, 2, and 3.

Table II-1. Latin Square - Frequency Regulator

Assembly Number	Order of Stress Application		
	1	2	3
1	5 g 30 min*	10 g 15 min	15 g 15 min
2	10 g 15 min	15 g 11 min	5 g 30 min*
3	15 g 8 min	5 g 30 min*	10 g 30 min

*Assumed Failure Time

Table II-2 Latin Square - Control Surface Actuator

Assembly Number	Order of Stress Application		
	1	2	3
1	10 g 30 min*	15 g 30 min*	20 g 11 min
2	15 g 15 min	20 g 30 min*	10 g 30 min*
3	20 g 30 min*	10 g 30 min*	15 g 15 min

Table II-3 Latin Square - Arming Computer

Assembly Number	Order of Stress Application		
	1	2	3
1	5 g 30 min*	10 g 30 min*	15 g 1.7 min
2	10 g 2.5 min	15 g 0.8 min	5 g 5.8 min
3	15 g 7.5 min	5 g 2.9 min	10 g 15 min

Test for Wearout

To test for the existence of wearout effects, it is necessary to adjust the mean life by varying K. If the mean life is estimated correctly for each stress level, then the estimated mean life for a given stress level will be approximately the same whether or not the unit had been tested previously. Where wearout effects, or age effects, are successfully compensated for, there will be no significant differences between the average values for each of the columns in the Latin square. If K is too large (too much influence given to age), then each mean life will be overestimated. Since the magnitude of the error is related to wearout, the columns to the right in the Latin square should be progressively larger. If K is too small, (too little influence

given to age), then each mean life will be underestimated. As before, the error is related to age, but now the estimates, and hence the column averages, will be progressively smaller.

The proper value of K was determined by an analysis of variance (table II-4) in which the natural logarithm of the mean life was used in the square. From the information shown in table II-5, a value of unity is the best estimate for K.

Table II-4 Analysis of Variance

Source of Variation	D.F.	Statistical Test
SS due to age effect SS_A	2	$\frac{SS_A}{SS_E}$ F(2,2)
SS due to stress effects SS_S	2	$\frac{SS_S}{SS_E}$ F(2,2)
SS due to different units SS_U	2	$\frac{SS_U}{SS_E}$ F(2,2)
Error SS - SS_E	2	
Total SS - SS_T		

Table II-5 Variance Ratios

Assembly	K	$\frac{SS_A}{SS_E}$
Frequency Regulator	1	1.8613
	2	12.4414
	3	16.2179
Control Surface Actuator	1	1.0000
	2	4.5068
	3	8.5969
Arming Computer	1	0.1949
	2	0.4141
	3	0.5395

Earlier studies indicated that the mean life could be approximated by

$$\theta = \epsilon^{AS + B} \tag{2}$$

where

S = vibration stress level

A,B = constants

An average of the three estimates for the mean life at each stress level was computed. These values were substituted into equation (2), which was expanded in a Taylor's series about initial estimates for A and B. The resulting values for A and B were used as new estimates in the Taylor's expansion. The iteration was continued until the desired accuracy was obtained. Values for A and B determined by this method are shown in table II-4, column 2.

A second estimate for A and B was obtained by taking the natural logarithm of the average of the mean life for a given stress level and fitting a curve by standard linear regression analysis. These values are shown in column 1 of table II-6.

Table II-6 Estimates for A and B

Assembly	Column 1		Column 2	
	A	B	A	B
Frequency Regulator	-0.1028	4.1253	-0.0992	4.0959
Control Surface Actuator	-0.0324	3.8185	-0.0391	3.9248
Arming Computer	-0.1309	3.2296	-0.0678	2.7727

Reliability Equations

The reliability for time T is given by

$$\text{reliability} = \epsilon^{-T^K \epsilon^{-(AS + B)}} \tag{3}$$

The average strength is defined as that stress level for which the reliability of the item is 0.50 when tested for a time period T. Substituting 0.50 for the reliability in equation (3), we have the following expression for the average strength as a function of time:

$$S = \left[K \text{ LOG } T - \text{LOG } (-\text{LOG } 0.5) - B\right] \div A \tag{4}$$

The reliability boundary, F, is the extreme stress level sustained by the equipment under service conditions. The safety margin, defined as the number of standard deviations which separate the average strength from the reliability boundary, is given by

$$\left[\frac{K \text{ LOG } T - \text{LOG } (-\text{LOG } 0.5) - 5}{A} - F\right] \div \frac{\sqrt{3}\,\sigma}{A} \tag{5}$$

where

σ^2 = residual variance arising from the estimates of A and B.

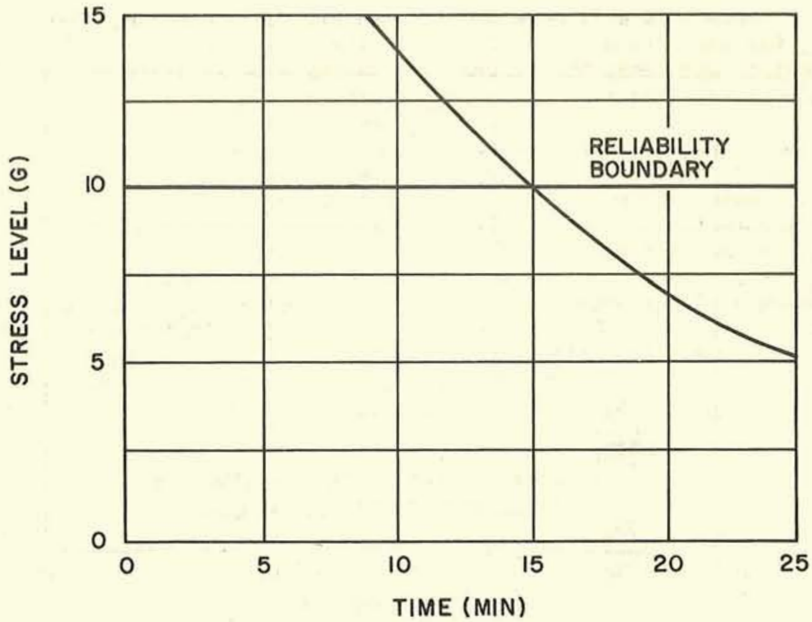


FIGURE II-1. AVERAGE STRENGTH, FREQUENCY REGULATOR

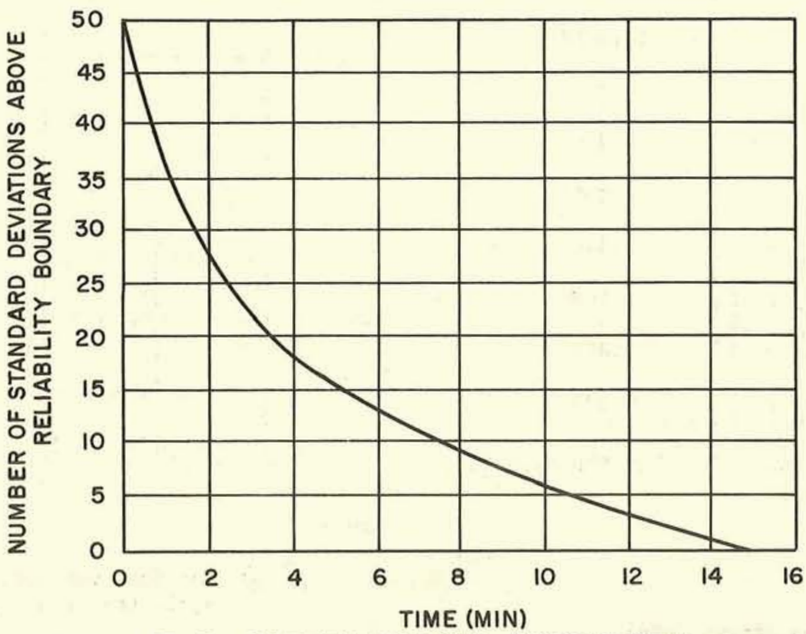


FIGURE II-2. SAFETY MARGIN, FREQUENCY REGULATOR

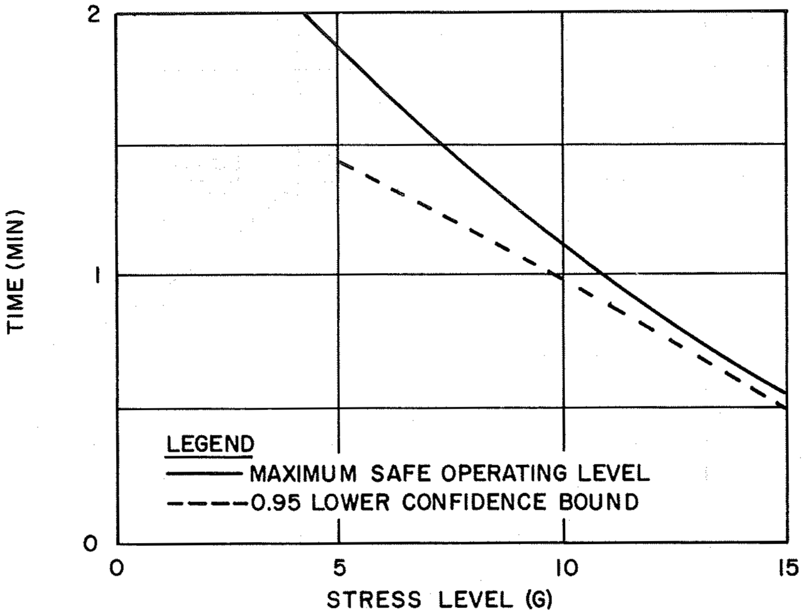


FIGURE II-3. MAXIMUM SAFE OPERATING LEVEL, FREQUENCY REGULATOR

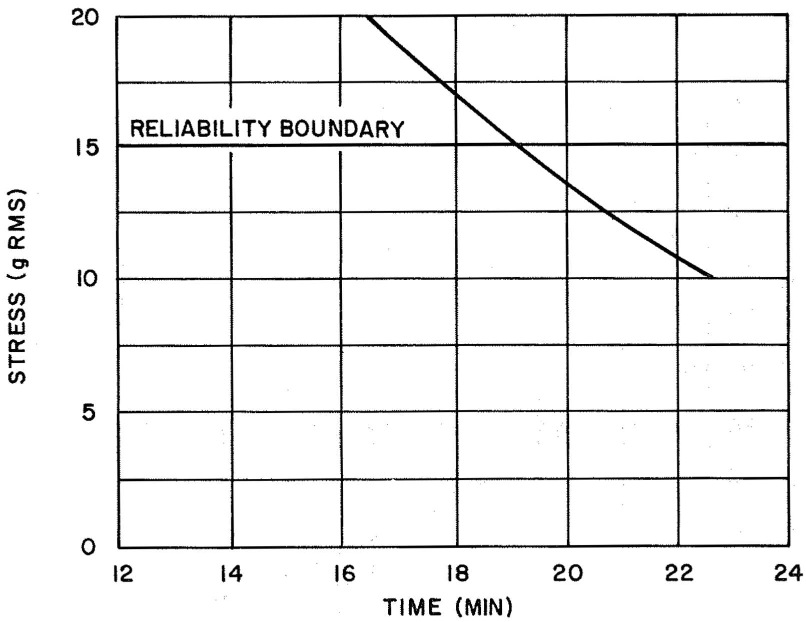


FIGURE II-4. AVERAGE STRENGTH, CONTROL SURFACE ACTUATOR

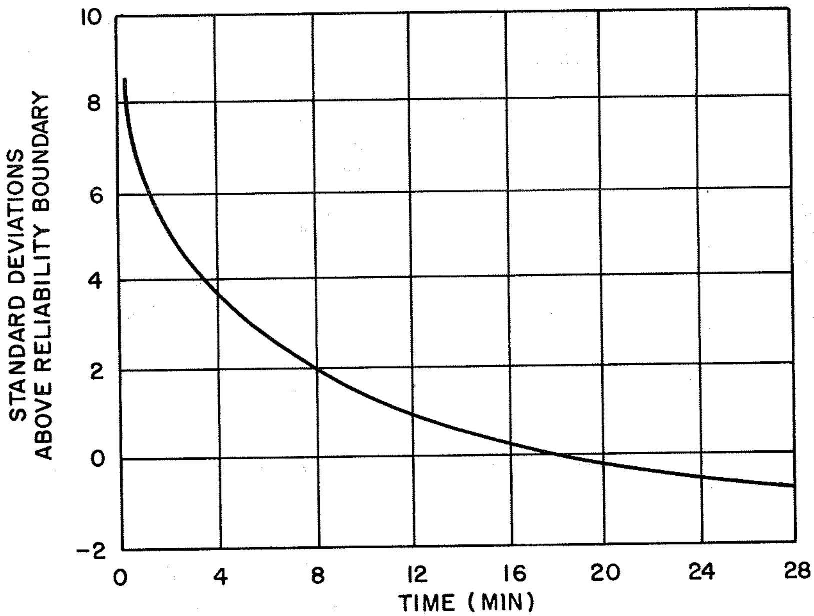


FIGURE II-5. SAFETY MARGIN, CONTROL SURFACE ACTUATOR

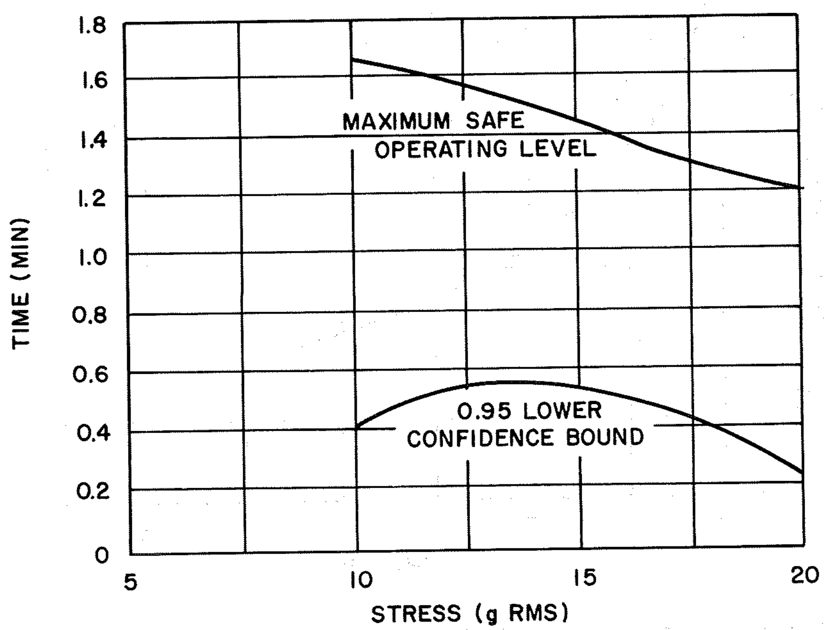


FIGURE II-6. MAXIMUM SAFE OPERATING LEVEL, CONTROL SURFACE ACTUATOR

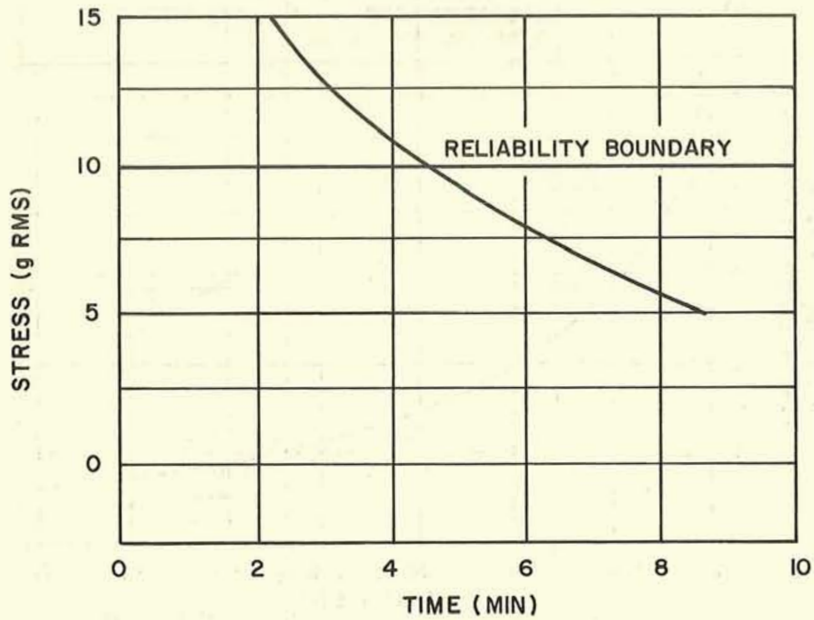


FIGURE II-7. AVERAGE STRENGTH, ARMING COMPUTER

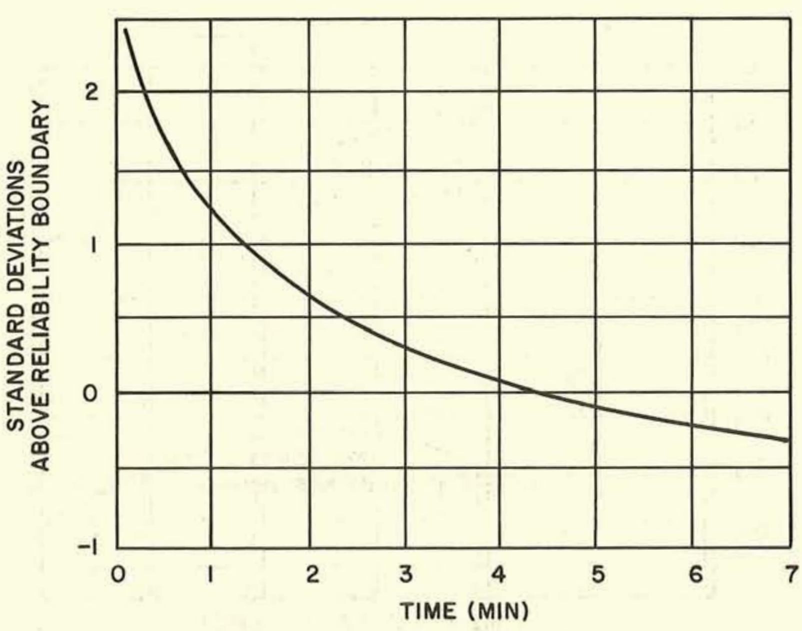


FIGURE II-8. SAFETY MARGIN, ARMING COMPUTER

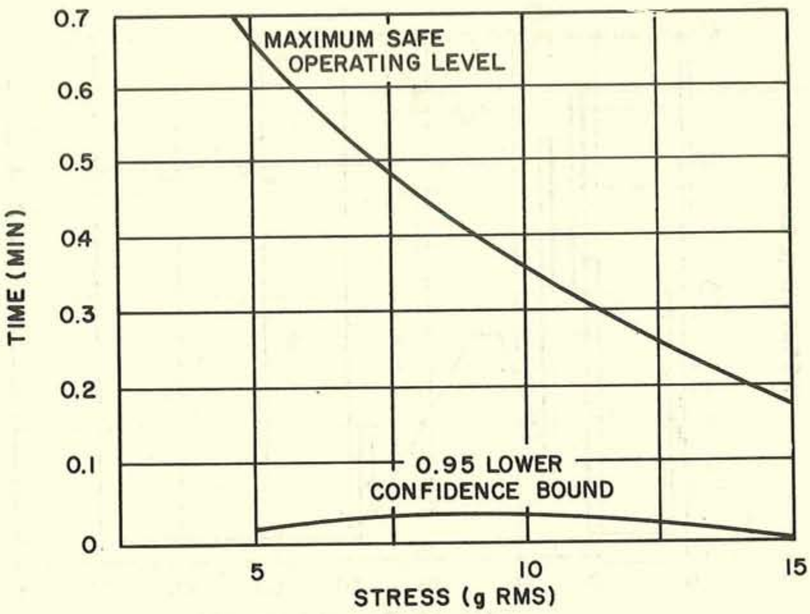


FIGURE II-9. MAXIMUM SAFE OPERATING LEVEL, ARMING COMPUTER

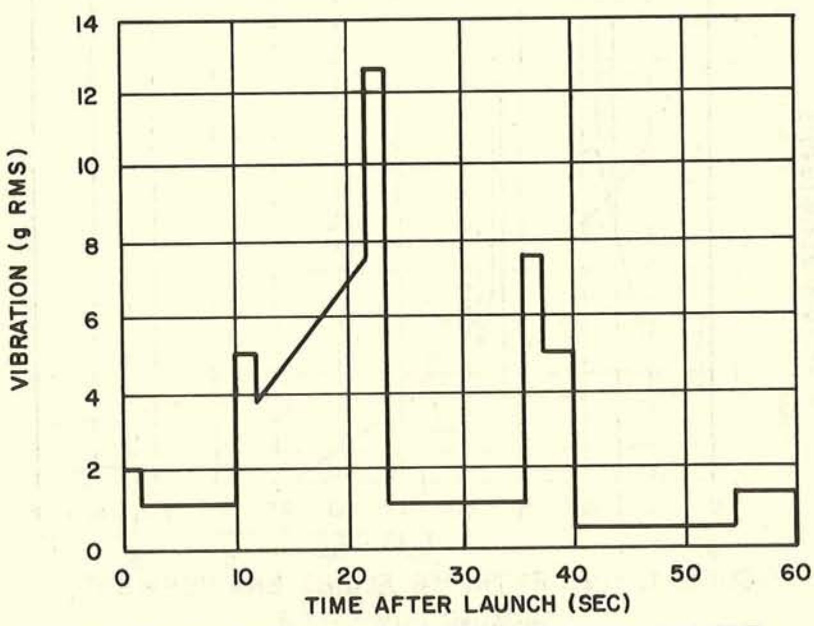


FIGURE II-10. EXTREME FLIGHT ENVIRONMENT FOR FREQUENCY REGULATOR, COMPOSITE FOR ROUNDS 37 AND 43

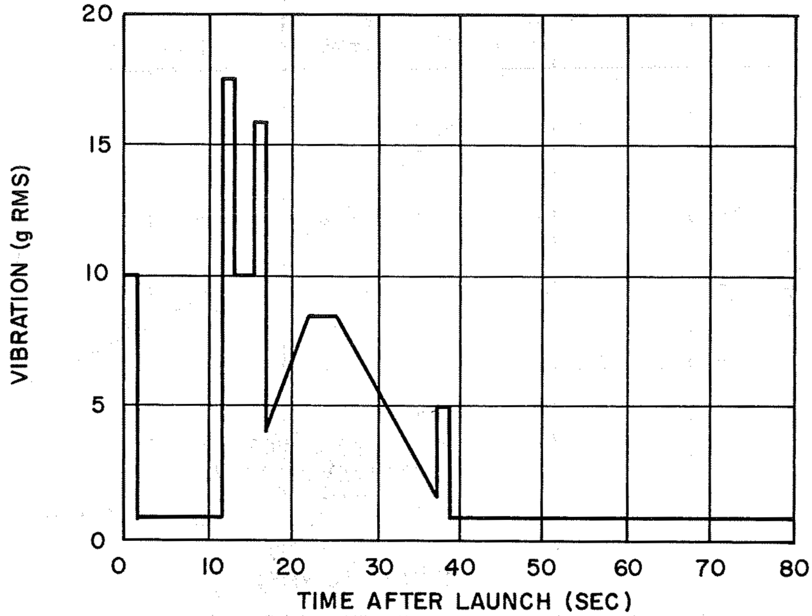


FIGURE II-11. EXTREME FLIGHT ENVIRONMENT, CONTROL SURFACE ACTUATOR

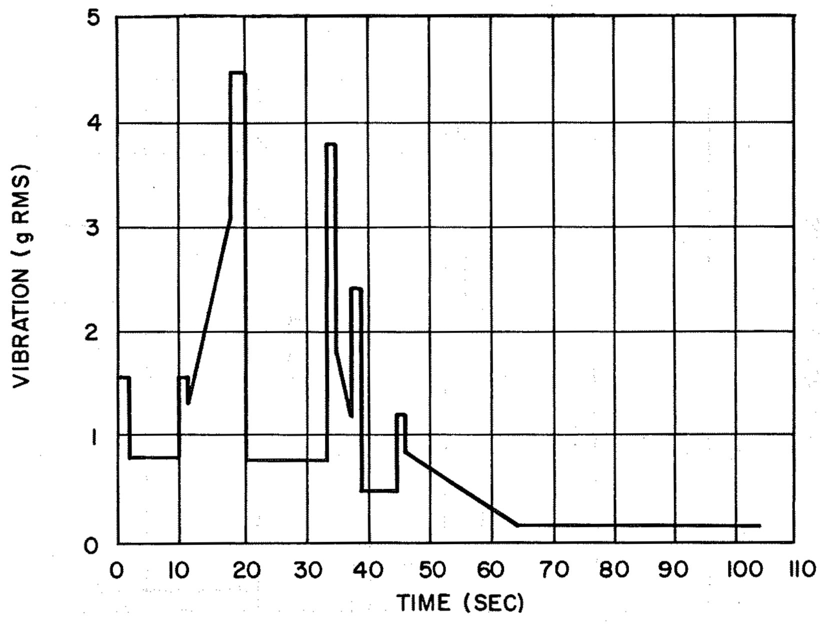


FIGURE II-12. EXTREME FLIGHT ENVIRONMENT, ARMING COMPUTER

If the reliability in equation (3) is 0.95, the corresponding stress, S, is defined as the maximum safe operating level (MSOL). The 95-percent lower confidence bound for the MSOL is given by

$$T = \left[(-\text{LOG } 0.95)\ \epsilon^{(AS + B - t_{0.95} H)}\right]^{\frac{1}{K}} \qquad (6)$$

where

$T_{0.95}$ = is the value in the "t" tables at the 95 percent level with one degree of freedom, and

$$H = \left[\sigma^2 \left(C_0 + C_1 S_L + C_2 S_L^2\right)\right]^{\frac{1}{2}}$$

$$C_0 = \frac{\sum_{L=1}^{3} S_L^2}{3 \sum_{L=1}^{3} (S_L - \bar{S})^2}$$

$$C_1 = \frac{-2\bar{S}}{\sum_{L=1}^{3} (S_L - \bar{S})^2}$$

$$C_2 = \frac{1}{\sum_{L=1}^{3} (S_L - \bar{S})^2}$$

Graphs of the average strength, safety margin, and MSOL for the frequency regulator used in the Sergeant missile are shown in figures II-1, II-2, and II-3, respectively. Corresponding graphs for the control surface actuator and the arming computer are shown in figures II-4 through II-9.

Flight Reliability

If the stresses during flight, ψ, are expressed as a function of time, then

$$\text{reliability} = \epsilon^{-\int_0^t \epsilon^{-(A\psi + B)} KT^{K-1}\, dt} \qquad (7)$$

where

T = time of flight

A graph showing the in-flight stresses, ψ, for the critical vibration axis of the frequency regulator is shown in figure II-10. Corresponding graphs for the control surface actuator and the arming computer are shown in figures II-11 and II-12, respectively. The flight reliability was determined by integrating equation (7) with the stress as shown in figures II-10, 11, and 12.

The flight reliability corresponding to the two different estimates for A and B is shown in table II-7.

Table II-7 Flight Reliability

Assembly	Flight Reliability (A and B are taken from table II-6)	
	Column 1	Column 2
Frequency Regulator	0.9916	0.9915
Control Surface Actuator	0.9867	0.9876
Arming Computer	0.9862	0.9812

Assemblies Having No Failures

The motor-generator, interconnecting box, cable assembly, and antenna were tested to the Latin square design. The vibration levels for the motor-generator were 5, 10, and 15 g. The interconnecting box, cable assembly, and antenna were tested at 10, 15, and 20 g.

Because there were no failures at any of the stress applications, the Latin square model could not be used. In view of this fact, the flight reliability was determined as follows:

Let the probability of success be $\frac{x}{m}$, where x is equally likely to have any of the values 0, 1, 2, 3 ... m. The chance that the first n trials should all be successful is

$$\frac{1}{m+1}\left\{\left(\frac{1}{m}\right)^n + \left(\frac{2}{m}\right)^n + \ldots + \left(\frac{m}{m}\right)^n\right\} = \frac{1}{N} \qquad (8)$$

When the event described by equation (8) has taken place, then $x \neq 0$. The respective probabilities that x has the values 1, 2, ... m become

$$\frac{N}{m+1}\left(\frac{1}{m}\right)^n, \ \frac{N}{m+1}\left(\frac{2}{m}\right)^n, \ \ldots \ \frac{N}{m+1}\left(\frac{m}{m}\right)^n \qquad (9)$$

and the chance of success at the (n + 1)th trial is

$$\frac{N}{m+1}\left\{\left(\frac{1}{m}\right)^{n+1} + \left(\frac{2}{m}\right)^{n+1} + \ldots \left(\frac{m}{m}\right)^{n+1}\right\} \qquad (10)$$

or

$$\frac{\left(\frac{1}{m}\right)^{n+1} + \left(\frac{2}{m}\right)^{n+1} + \ldots \left(\frac{m}{m}\right)^{n+1}}{\left(\frac{1}{m}\right)^{n} + \left(\frac{2}{m}\right)^{n} + \ldots \left(\frac{m}{m}\right)^{n}} \qquad (11)$$

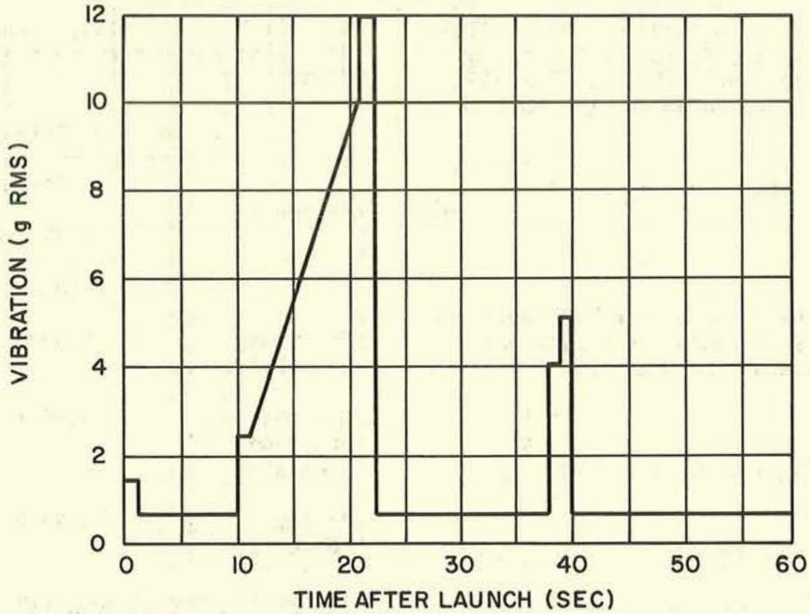


FIGURE II-13. FLIGHT ENVIRONMENT, MOTOR-GENERATOR

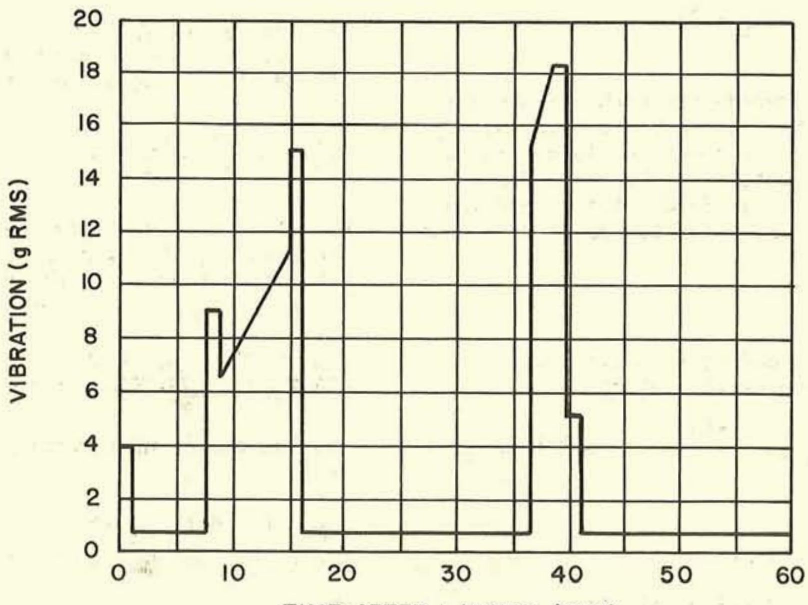


FIGURE II-14. FLIGHT ENVIRONMENT, INTERCONNECTING BOX

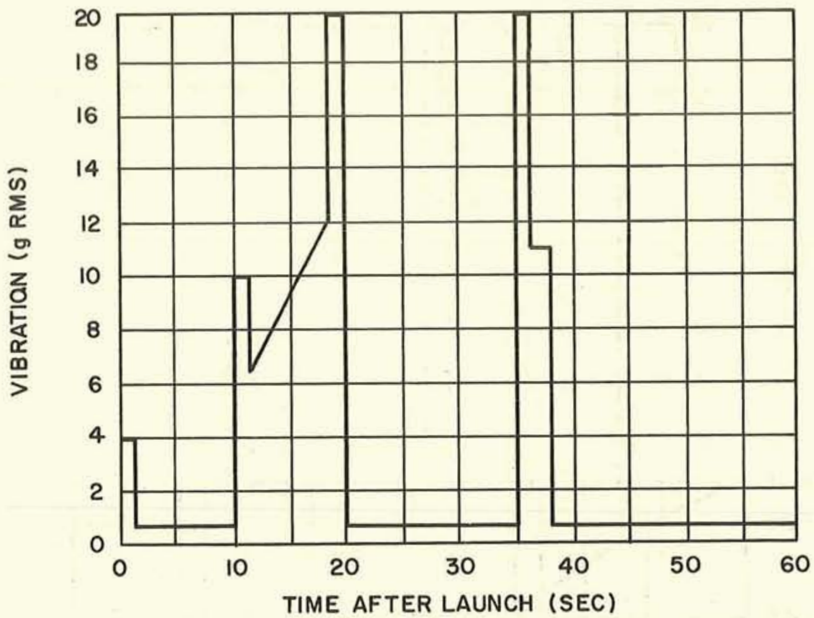


FIGURE II-15. FLIGHT ENVIRONMENT, CABLE ASSEMBLY

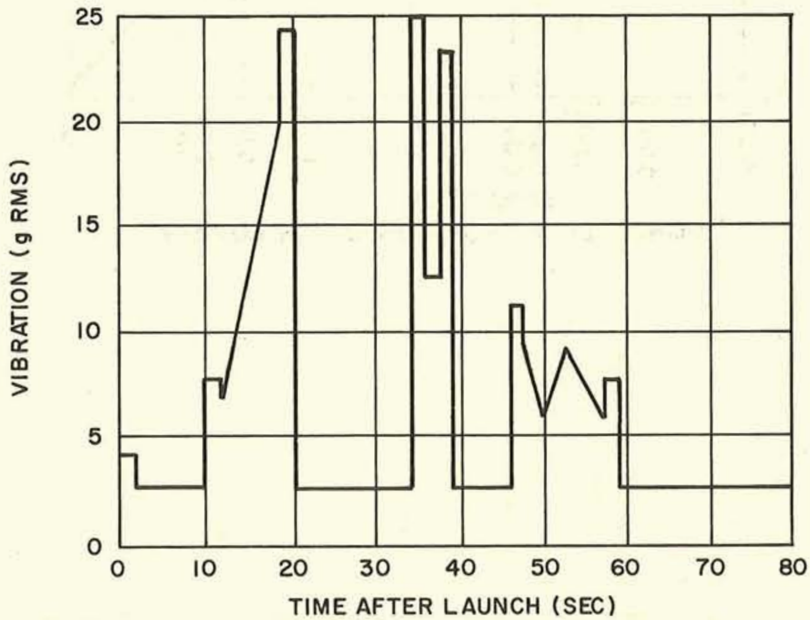


FIGURE II-16. EXTREME FLIGHT ENVIRONMENT, ANTENNA

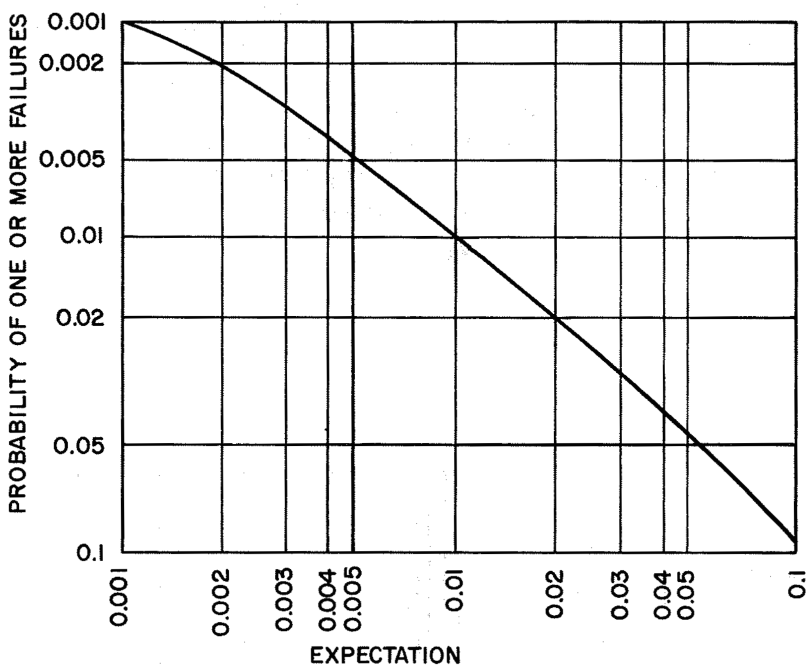


FIGURE II-17. POISSON DISTRIBUTION

When the numerator and denominator of equation (11) are divided by m, the denominator can be written as

$$\frac{1^n + 2^n + . . . + m^n}{m^{n+1}} = \frac{1}{n+1} \quad \frac{m^{-1}}{2}$$

$$+ \frac{B_1 nm^{-2}}{2!} \quad \frac{B_2 n(n-1)(n-2) m^{-4}}{4!} + . . . \qquad (12)$$

where B_1, B_2. . . = Bernoulli's numbers.

Equation (12) can be rewritten as

$$\frac{1}{n+1} + \text{terms involving negative powers of m} \qquad (13)$$

Therefore, if m is increased without bound,

$$\frac{1^n + 2^n + . . . + m^n}{m^{n+1}} = \frac{1}{n+1} \qquad (14)$$

Expanding the numerator of equation (10) in the same manner and letting m increase without bound gives

$$\frac{1^{n+1} + 2^{n+1} + ... + m^{n+1}}{m^{n+2}} = \frac{1}{n+2}$$

Hence the chance of success at the (n + 1)th trial is $\frac{n+1}{n+2}$ (15)

At the 95-percent level, the value of n is 18. Each item was tested for a total time of 90 minutes; hence an extimate for the mean time to failure is 95 minutes.

The flight environments for the motor-generator, interconnecting box, cable assembly, and antenna are shown in figures II-13 through II-16, respectively. Based upon the Poisson distribution and an expectation of 0.003, the flight reliability is approximately 0.997. (See figure II-17 for selected values from the Poisson distribution.)

Statistical Limitation

The 95-percent upper and lower confidence bounds for the MSOL form a hyperbola whose asymptotes intersect at the means for the time and stress. Only the 95-percent lower confidence bounds are shown in the figures for the MSOL. As the sample size increases, the slopes of the asymptotes approach the slope of the regression line. In fact, for large samples the confidence bounds are approximately parallel with the regression line.

For small samples the hyperbolic nature of the confidence bounds is greatly exaggerated, reflecting the lack of confidence at the ends of the stress intervals. For the previously discussed assemblies this limitation is apparent.

PART III. CONCLUSIONS AND RECOMMENDATIONS

The basic statistical test philosophy proved to be readily adaptable to practical test application on Sergeant missile assemblies.

To preclude biasing reliability indices too conservatively for "no-failure" type assemblies it was necessary to develop a new statistical analysis.

Results of the test indicated that Sergeant missile assemblies are not subject to wearout effects from the environmental tests.

The repeated test-to-failure program identified design, component, and quality control type defects that were not discovered by previous type-approval and flight acceptance test programs.

The computed in-flight reliability calculated from the repeated test-to-failure program agreed with the reliability as demonstrated in the R & D missile flight test program.

Bibliography

1. White, D., Operational Reliability and Maximum Safe Operating Levels for Expensive Equipment, Proceeding of the Sixth Joint Military-Industry Guided Missile Reliability Symposium, presented February 15-17, 1960, El Paso, Texas.

N62-16912

A METHOD FOR DETERMINING THE COST OF FAILURES

David E. Van Tijn
ARINC Research Corporation
Washington, D.C.

Summary

Cost predictions for weapons systems are based on the same general principles, and developed by the same general techniques, as reliability predictions for equipments. Therefore, the step-by-step procedure for developing a mathematical model for cost allocation -- on which the cost predictions are based -- is analogous to the well-established procedures for developing reliability allocation models. This paper presents a sequential set of rules for establishing a cost model, exemplified by application to an actual Air Force weapons system.

The model developed for a particular support system will allocate the various expenditures for the equipment being supported. Expenditures fall within the categories of Investment, Manpower, Supplies, and Time.

A discussion of the theory behind cost allocation and predictions precedes the presentation of the rules for development of a cost model.

Introduction

Cost predictions for the support of weapons systems are evolved in much the same manner as reliability predictions for equipments. The three basic data-inputs to each are of the same general nature. A reliability prediction considers (a) characteristics of parts, (b) the collective functioning of parts, and (c) the effects of part variations on the equipment as a whole. A cost prediction considers (a) actions of individual personnel, (b) features of the weapons system support organization, and (c) the skill of support personnel, as reflected in organizational efficiency.

This analogy does not suggest that support costs are independent of equipment characteristics, any more than reliability is independent of the properties of metals or of the dielectric behavior of insulators. However, just as failures occur when some basic quality of a material is changed out of tolerance, so costs are incurred when someone performs an action -- fixes an equipment, purchases a part, etc. The analogy can be carried further. Major contributions of any reliability prediction (in the course of its development) are the detection of design features which may tend to make the equipment prone to failure, and the location of areas in which redundancy can be employed to advantage. Similarly, cost studies will bring out improved methods of organizational controls. Evaluation of the cost of each support action will focus attention upon those organizational features and standard operating procedures which incur more than their fair share of costs.

A final parallel between reliability and cost is in the methodology one employs in the study process. The reliability of an equipment depends upon its detailed structure; for this reason, the related prediction theory consists of a series of instructions which, for a given equipment, will outline how to construct its reliability model. Likewise, one can follow a documented procedure for constructing a cost function for a given support organization. The inputs to a cost prediction are the costs of actions, materials, and personnel, and the frequency with which the equipment forces support action.

At this point, the cost analyst diverges from the reliability engineer. The actions of men which the former must observe are carried out in the open, and sophisticated systems exist for keeping track of relevant events. Therefore, cost analysis is more a problem of handling all of the information generated in the operation of a support organization than a problem of conducting basic research. For the reliability engineer this situation would be analogous to having an oscilloscope hooked up to every wire, a micrometer to every wearing surface, etc. From this point of view, a cost analyst is indeed in a fortunate situation.

From another point of view he is not so fortunate. Although certain phases of the support organization can be observed in isolation, the only way in which the cost of the time which materials spend in the system can be accounted for is by observing the system as a whole.

The cost analyst has two further disadvantages vis-a-vis the reliability engineer:

(1) The data concerning on-the-job performance of personnel are also used by their superiors to

evaluate this performance. Hence the complete objectivity (and accuracy) of such data is dubious, at best; such data must always be investigated, and inaccuracies accounted for in the final results.

(2) Among the factors inflating the size of a supply system are the delay-times which occur between the different stages of the system. These delay-times must be assigned a cost, charged to the activity responsible for them. One way of doing this is by counting the flow of new purchases at critical points. However, the cost analysis may be complicated by a considerable amount of interdependence between the different parts of the support system, again postponing the full usefulness of the cost model.

In the third section of this paper are listed some of the rules for constructing cost models, exemplified by application to an actual Air Force support system. This presentation is preceded by a short identification of costs, and a discussion of the limitations of the present methodology.

In the final section is given a brief review of the manner in which cost information developed by these rules can be useful in the decision-making processes of the services.

Expenditure Headings

A model developed for a particular support system will allocate the various expenditures for the equipment being supported. The following paragraphs discuss what these expenditures are.

Investment

The "Investment" category includes most of the fixed expenditures for bases and maintenance and supply facilities; and for the first cost of weapons and their initial stocks of supplies. In the new DOD costing procedure, this category does not include operating expenses. Therefore, no rules are given herein for allocating Investment expenses.

Manpower

This heading is important for two reasons: support personnel are in chronically short supply, and their pay and allowances constitute an expenditure equivalent to that for supplies and for the weapons themselves.

Rules are presented in the last section which allocate all types of manpower -- direct, supervisory, managerial, and administrative -- within the support organizations. The men themselves have a support system that provides them with training, subsistence, re-enlistment bonuses, and retirement pay. This secondary support system will be reflected in the cost model as an increase in the cost of a man-hour's labor. The methods of computing this increase, and its size, will be left out of this account; the cost of a man-hour's labor in the different organizations, ranks, and grades will be regarded as a parameter of the model.

Supplies

Supplies are the first source of expenditure coming to mind in the consideration of support costs. Supply costs form the third visible source of expenditure.

Time

Time-delays act to inflate the supply system. They contribute an invisible source of expenditure that must be charged to the responsible activity.

Procedure for Constructing An Allocation Model

A step-by-step procedure for developing a cost-allocation model is presented in the following section. Application of the sequential set of rules will yield a model for making monthly estimates of the cost of supporting a particular weapon system. The cost will be distributed among the various units* of the system, with a residue left over for assignment to parts which cannot be rationally distributed back to any particular units. The allocation takes the form,

$$\text{Total cost} = \text{Cost of unallocated parts} + \sum (\text{cost of units}) \qquad (1)$$

The costs of units are further subdivided into costs at different echelons; at each echelon,

$$\text{Cost of unit} = \text{Cost of equipment} + \text{Cost of maintenance} + \text{Cost of supply}. \qquad (2)$$

The connection between echelons is made at two points: (1) the cost charged the lower echelon is dependent upon events at higher echelon; (2) some of the costs at the higher echelon arise from units charged back from lower echelons to cover

*The term "unit," as used here, refers to the weapons system or any of its identifiable subsystems.

inventory inflation caused by increased lags in deliveries from the higher echelon.

At each echelon, continuing from Equation (2), maintenance and supply costs are made up of manpower and material expenditures:

Cost of maintenance = Cost of manpower + Cost of parts used in maintenance + Cost of new units charged to maintenance. (3)

Finally, the manpower cost has been derived in such a way that the contribution of different organizational features and subdivisions to overhead is clearly established:

Manpower cost = F(overhead factors from different sources) (4)

where the function, F, includes the organizational structure, and the factors represent the extent of overhead incurred in the overhead sources established by this organization.

Allocation Rules

As previously stated, the rules presented in this section can be used to construct a cost allocation model which will account for most of the costs incurred in the support of weapon systems. The rules are designed for piece-wise construction of a model, i.e., different parts of the support organization at different echelons will be represented by different terms. The way the pieces are developed ensures maximum sensitivity to actual events, procedures, and organizational features.

Rule 1

Every weapon system support organization will contain maintenance and supply systems, and usually several echelons of each.

Draw a flow diagram representing the flow of parts and spares, and of repairable and serviceable items between the various maintenance and supply organizations. Be sure to note the time delays.

Example: The gross flow of parts and units on an Air Base is diagrammed in Figure 1.

From the flow diagram, derive a formula which will have the form:

Total Charge per echelon = Equipment charge + Maintenance charge + Supply charge (1)

Note that Total Charge includes all units and parts, and all maintenance actions. The equipment charge represents, for example, the cost of condemned equipment, which cannot be ascribed to either organization. With the aid of the diagram write for each term in each echelon an equation of the following form, where the terms and time-delays are identified with organizations on the diagram.

Maintenance Charge = Manpower charge + Materials charge + Charge for time delays in the maintenance system. (2)

and

Supply Charge = Manpower charge + Materials charge + Charge for time delays in supply system. (3)

Example (cont'd): (a) In Figure 1, the delay in the base repair of units is marked (1), the delay in delivery of NRTS units to base supply is marked (2).* (b) The time delays chargeable to supply in the example are the ones marked (3), delivery of bad units, and (4) and (5), which are delays in the ordering of new parts and units from depot.

Rule 2

Step 2.1

Break down the manpower charges among the different units of the weapon system.

This step represents a major effort for each term representing organizations. It has been accomplished for the maintenance manpower at air bases. A detailed description of the procedure is contained in References 2 and 3. A guide to performing this task is presented below.

---

*The method of computing charges for time-delays is described in Rule 3.

Step 2.1.1

Obtain a detailed organization chart. Draw the flow of work assignment. Establish which organizations support each unit, and which overhead functions support the direct labor in each sub-organization.

Example (cont'd): Figure 2 is a diagram of part of a base maintenance organization. Figure 3 diagrams the flow of men, materials, and control documents at an Air Base.

Step 2.1.2

Estimate the amount of direct labor spent each month in each subdividion of the organization on each type unit (and type part, if it is a supply organization). Estimate the number of actions per month taken in support of each type unit.

Example (cont'd): At an Air Base, the values mentioned in Step 2.1.2 are obtained from the AFM 66-1 Maintenance Data Card Systems.*

Step 2.1.3

Divide the overhead labor into two classes: (1) Administrative, which is incurred for each action, (2) Managerial, which is incurred for each man.

Compute in each subdivision a per-action and per-manhour overhead time charge, as well as an overhead cost charge, using the information from Step 2.1 as to which actions benefit from particular overhead centers.

Step 2.2

Figure in the dollar-cost of manpower.

Step 2.2.1

Estimate the amount of overhead labor spent each month in each payclass and overhead labor category, in each subdivision of the organization

Example (cont'd): At an Air Base these quantities are obtained from the AFM 66-1 Exception Time Card System.

Step 2.2.2

Estimate the cost of an hour's labor in each category in each subdivision of the organization.

Example (cont'd): A weighted average of the actual hourly pay in each Air Force workcenter is available from the base records.

Step 2.3

Combine into manpower and dollar-charges.

Step 2.3.1

After accumulating administrative-type charges between management levels, a series of overhead time and cost factors, representing the overhead incurred at different levels for that subdivision, can be produced for each subdivision of the organization. This procedure yields, after accumulation, a listing for two levels of management, of the form

Subdivision	Admin. Time	Mgmt. Time	Admin. Time	Mgmt. Time
Identity	a	m	a'	m'

Subdivision	Admin. Cost	Mgmt. Cost	Admin. Cost	Mgmt. Cost
Identity	c_a	c_m	$c_{a'}$	$c_{m'}$

Subdivision	Direct Labor Cost
Identity	c_l

Example (cont'd): At an Air Base, scheduling and motor vehicle time would be administrative type charges, and management would be a managerial type charge.

An example of cost-factor listing is given below.

Workcenter No.	a	m	a'	m'
26350	1.62	0.107	0.60	0.036

c_a	c_m	$c_{a'}$	$c_{m'}$	c_l
2.55	2.70	1.64	4.01	1.21

---

*In principle, these two systems give all the information needed; (they do seem to provide 100% coverage). ARINC Research Corporation is currently investigating their accuracy. A test of the sensitivity of costs to the type and degree of inaccuracies found will be instituted.

(Numbers are obtained from February 1962 Data for Walker AFB.)

Step 2.3.2

Compute the per-action time and cost charges, by the following formulas:

$$t = P + Ql, \qquad (4)$$

where t = time per action,
l = direct time on this action;

and

$$C = C_p + C_{Ql}, \qquad (5)$$

where C = cost per action.

Hence, P, Q, C_p and C_Q contain the overhead time and cost charges for the subdivision by which the action was performed. If these are a, a', c_a, $c_{a'}$ for administrative charges, and m, m', c_m, $c_{m'}$ for management charges, for two levels of management, then:

$$P = a(1+m)(1+m') + a'(1+m') \qquad (6)$$

$$Q = (1+m)(1+m') \qquad (7)$$

$$C_p = a \cdot c_a + a' \cdot c_{a'} + c_m \cdot m\, a + c_{m'} \cdot m'(a' + (1+m)a) \qquad (8)$$

$$C_Q = C_l + C_m \cdot m + C_{m'} m'(1+m) \qquad (9)$$

Add the per-action costs and times over all similar units for the month considered. Compute average figures for the cost, time, and direct labor.

Example (cont'd): Part of such a listing is given in Table 1. The first column identifies the units. The succeeding columns are, in order: time (with overhead), cost, direct labor, number of units handled, average time, average cost, average direct labor.

Rule 3

Allocate the monthly material costs to units, and compute the charges for time delays. By the setting up of check points where delays may result in the accumulation of stock, new acquisitions can be charged to stock accumulation on arrival. This procedure automatically charges time-delays to the responsible activity. The appropriate procedure is as follows:

Step 3.1

(a) Obtain a count of the number of serviceables for each type of unit delivered to the supply organization of an echelon, and the cost per unit (for cost per unit, see Rule 4).

(b) Obtain a count of the number of each type of part delivered to the supply organization at each echelon, and their costs.

(c) Obtain a count of the average monthly backlog for each type unit in the maintenance organization, divided into an "awaiting parts" class and an "awaiting maintenance" class.

(d) Obtain a count of the number of each type unit condemned by the maintenance organization.

(e) Obtain a count of the number of each type unit returned to a higher echelon for maintenance. If necessary, distinguish between those returned for legitimate reasons, those returned for specious reasons, and those returned for lack of parts.

(f) If there is a parts stockroom serving maintenance directly, obtain the cost of parts delivered to this stockroom during the month.

(g) Obtain the number of units and parts of each type on back order.

(h) Obtain the cost of parts used to repair each type of unit during the month, distinguishing between those which came from a maintenance stockroom, and those which came directly from supply. Only units and parts received from supply are charged.

Units are charged by the following procedure:

(a) Units received are charged against equipment, up to the number that are either condemned or sent for maintenance to higher echelon for legitimate reasons.

(b) If any units are left, they are charged in the following sequence:

(i) Against maintenance, up to the number returned for maintenance to higher echelons for specious reasons.

(ii) Against supply, up to the number returned for maintenance to higher echelon because of

lack of parts, provided the parts have been on back order more than a month.

(iii) Against maintenance, up to the average monthly backlog awaiting maintenance.

(iv) Against supply, up to the number which are awaiting parts, for which the parts have been back-ordered for less than a month.

(v) Against the higher echelon supply, up to the number that have been either

(i) on back order, or

(ii) awaiting maintenance for parts or sent for repair for lack of parts, with the parts back ordered a month or more.

(vi) Against supply.

Example: Suppose on an Air Base, for a particular month, fifteen units costing $1000 apiece are received from the depot, and counts are as follows:

(a) Three are condemned and two returned to depot because repair was not authorized.

(b) Two are returned for repair to depot because of an excessive work backlog.

(c) None are sent to depot for repairs, because of lack of parts.

(d) The average monthly backlog awaiting maintenance is three.

(e) Two are in maintenance backlog awaiting parts, but for one unit the parts have been on back-order for more than a month.

(f) Two units had been on back order when the fifteen arrived.

Then by Rule (a), five are charged to equipments;
by Rule (b), two of the ten remaining are charged to maintenance;
Rule (c) does not apply;
by Rule (d), three of the eight remaining are charged to maintenance;
by Rule (e), one of the five remaining is charged to supply;
by Rule (f), three of the four remaining are charged back to the depot;
by Rule (g), the one remaining is charged to supply.

Hence the total charges are:

To Equipment	$ 5,000
To Maintenance	5,000
To Supply	2,000
To Depot	3,000
Total Charge	$15,000...

... which was the expenditure made by the base.

The base stock of the unit has risen by ten, of which three are needed because of delays at depot (two back-ordered, and one awaiting parts which are back-ordered), and the other seven are needed to cover delays in maintenance and supply.

Step 3.2

Parts are charged as follows:

(a) Parts used in equipment repair are charged against equipment. Distinguish for each part type between those which came from a maintenance stockroom and those which came from supply.

(b) Maintenance is charged with parts delivered to the maintenance stockroom, less parts from the stockroom charged to equipment.

(c) Supply is charged with the remaining parts, less those (1) charged to the maintenance stockroom, (2) charged to equipment which came from supply, and (3) on back orders for a month or more.

(d) Depot is charged with parts on back-order for a month or more.

(e) Charge as much as possible of the parts costs against particular units.

Example: Suppose twelve parts of a type arrive during the month, of which six are delivered to bench stock. Then suppose six are used, four from bench stock, and two from base supply, one of which had been on order for six weeks. If the parts cost $10 each, then the following charges are made:

To Equipment	\$ 60
To Maintenance........\$60-40=	20
To Supply......\$120-60-20-10=	30
To Depot.....................	10
Total.....................	\$120

Again, the equation balances, for the base stock has risen by six items, of which two augment the maintenance stock, three the base-supply, and one covers the increased time-lag in delivery from depot.

Step 3.3

Add the per-unit materials and delay costs obtained from Step 3.1 to the costs obtained by Step 3.2, which is chargeable to units, to obtain a total per-month cost of the unit on the particular station.

Not all the parts costs obtained by Step 3.2 will in general be chargeable to units; some will often have to go as an overhead charge against the support system.

Rule 4

To find the per unit cost of units arriving at a supply point, proceed as follows:

Step 4.1

At the lowest echelon, only units arriving from outside are assigned a price. Units put back into stock after repair are not priced, nor are those units counted in charging materials costs to activities.

Step 4.2

At higher echelons, only units leaving for other supply points are assigned a price. Where units arrive from still higher echelons, or from maintenance at the same echelon, the price assigned will be a weighted average of the price charged for new units, and the cost of maintenance performed at that echelon on repaired units. The cost of maintenance includes handling and delays, as described in Rule 3.

Example: If during one month, 100 new units arrive at a depot from a manufacturer at \$1000 apiece, and 50 from depot maintenance which have cost \$400 apiece, then, for that month,

Total Cost of Units =

$$\frac{(100 \times \$1000) + (50 \times \$400)}{150} = \$800.$$

Future Development and Present Use

Present Status of Model Development

In the Introduction, a parallel was drawn between reliability theory and cost analysis. The rules in the preceding section are of the same form as the rules for constructing reliability models. Several distinctions, however, can be noted between the present states of the two arts. A reliability text,* after stating rules for modeling, will discuss statistical distributions which failures may follow, and mathematical methods of finding the failure distributions of more complicated systems from simpler ones. Due emphasis is given to the increase in reliability which may be obtained by introducing redundancy. For cost analyses, however, historical information on costs, distributed into the categories described in the foregoing rules, is very difficult to obtain. On the other hand, the building up of the costs of more complicated systems from the costs of its constituents is primarily an additive process, which is much less complicated than the combinatorial processes for reliability models. Finally redundancy, which introduces many of the difficulties in reliability analysis, is not a recommended method of cost reduction.

Present Use of Model Parts

The rationale from which the allocation rules were derived was to view cost information as indispensible to management control and decision-making. Consequently, at each level of management, the cost-information obtained will be sensitive to the actions controlled by management, and to its decisions. The higher the level of management, the greater the scope of the organization controlled and the decisions to be made. Correspondingly less detailed information will be needed. However, implicit in the use of aggregated information for making large-scale decisions is the assumption that the costs which have been aggregated are optimum and that lower-level decisions will be made from more detailed information.

The type of model described herein does two things: it develops cost data sensitive to the smallest piece of equipment and the lowest management level that can be distinguished in the data, then gives rules for aggregating these costs to successively larger pieces of equipment and higher levels of management. Each

*See, for example, Reference 4.

major piece of the model, as it is developed, will serve the control and information needs of a major management level. Thus, the model which distributes maintenance manpower at an airbase exhibits overhead costs and workloads at all lower levels of management. If introduced as a routine method in the digestion of base maintenance data, the model will furnish the cost part for any comparison of the cost-versus-effectiveness of identical organizations on different bases, and of different organizations on the same base.

Use of The Complete Model

Once the complete model has been developed and historical costs in the various categories accumulated, information will be provided at all levels of management of support systems. For current systems, the model will aid in the following functions.

Management of Current System The model will provide:

(1) Comparative cost data on the operation of major subordinate organizations.

(2) The complete cost of the present support of units, to ascertain which units might repay engineering changes.

(3) Factors which measure the elasticity of support costs to the frequency of unit failures, and the direct labor time required for repair. These can be used to evaluate the savings to be obtained from projected engineering changes.

(4) Information needed to compare the costs of maintenance at different echelons; e.g., which repairs are made cheaper at depot, and which at base level.

(5) Information needed to trade off possible support savings against increases in fixed investment, e.g., the introduction of new test equipment.

(6) A simulation tool with which suggested changes in the support organization can be evaluated before they are put into effect.

Of course, many of the tradeoffs listed above are now made, and made every day. However, the cost part of the equation is usually obtained with great trouble on an ad hoc basis, and used long after the circumstances on which it was based have changed. The kind of model described would automatically provide the information needed. It would therefore be more often used than circumvented, and would be current. The model would provide, on a routine basis, the information which management needs.

Planning Good current information is necessary for good planning. From sufficient support-cost information -- sensitive to equipment characteristics, organizational features, and the characteristics of manpower -- it will be possible to derive equations to predict support costs of future systems. If derived in this way, the equations will depend on parameters which will change with new weapons systems; hence, the equations will be easy to adjust to radically new concepts.

In this area perhaps the biggest payoff will come. With the new planning concept* which depends upon estimating the long-term costs of programs, good equations for future costs have become indispensable to bringing a concept to fruition. The best, as well as the easiest, procedure is to base such predictions on a routinely-provided series of data, which are both sensitive and current.

References

1 Selective Bibliography on Program Budgeting in the Department of Defense, issued to participants in the Costing Work Group at the 9th MORS, Ft. Monroe, Va., April 1962.

2 Special Interim Report on Cost Studies, D. E. Van Tijn, ARINC Research Publication No. 159-1-250, dated 14 July 1961.

3 Second Special Report on Cost Studies, D. E. Van Tijn, ARINC Research Publication No. 206-1-277, 29 January 1962.

4 A Revised Course in Reliability Theory and Practice, ARINC Research Corporation Publication No. 123-7-196.

5 Novick, D., System and Total Force Cost Analysis, The RAND Corporation, Research Memorandum RM-695, dated April 15, 1961.

---

*See, for instance, References 1 and 5.

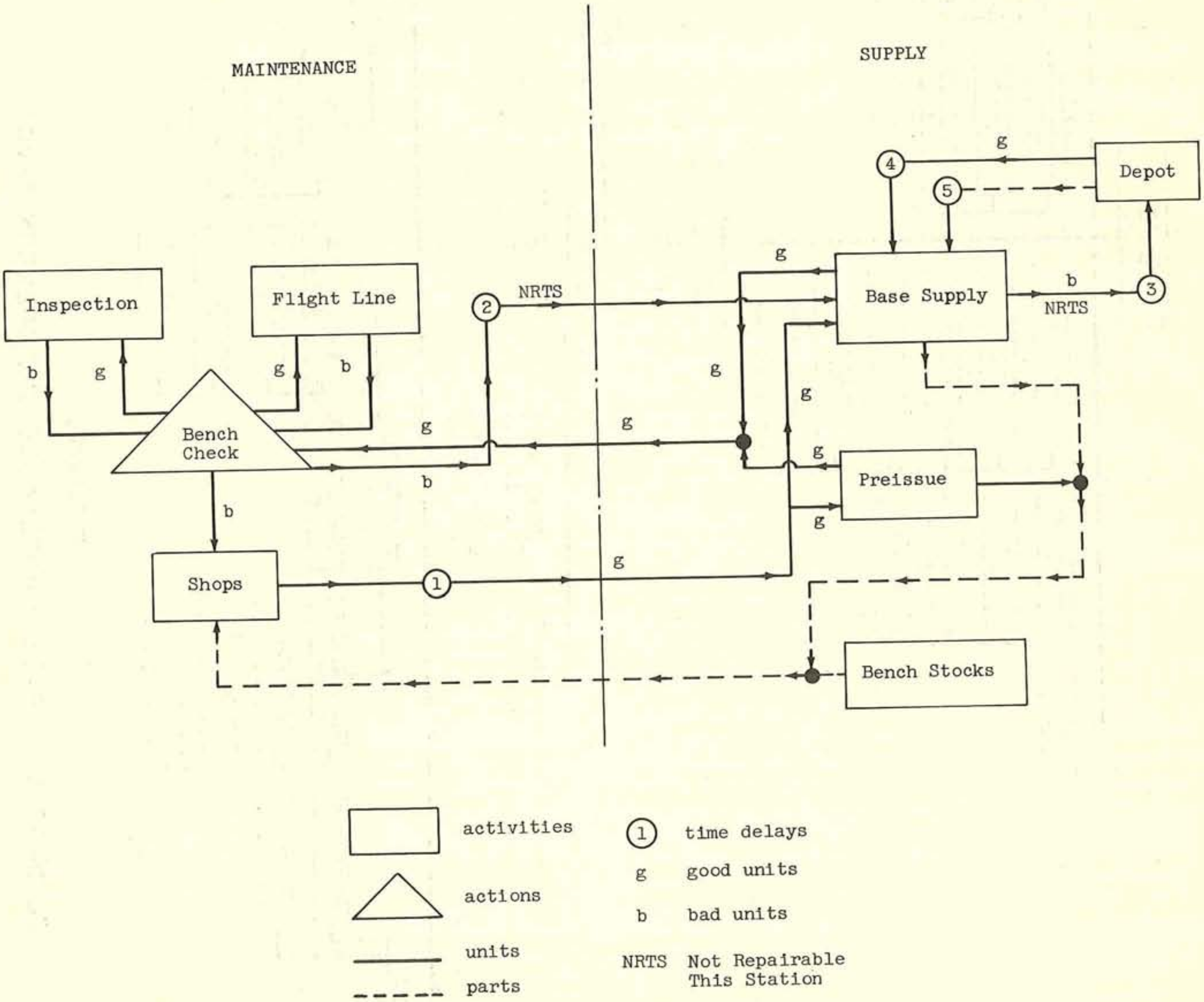


FIGURE 1

GROSS FLOW OF UNITS AND PARTS ON AN AIRBASE

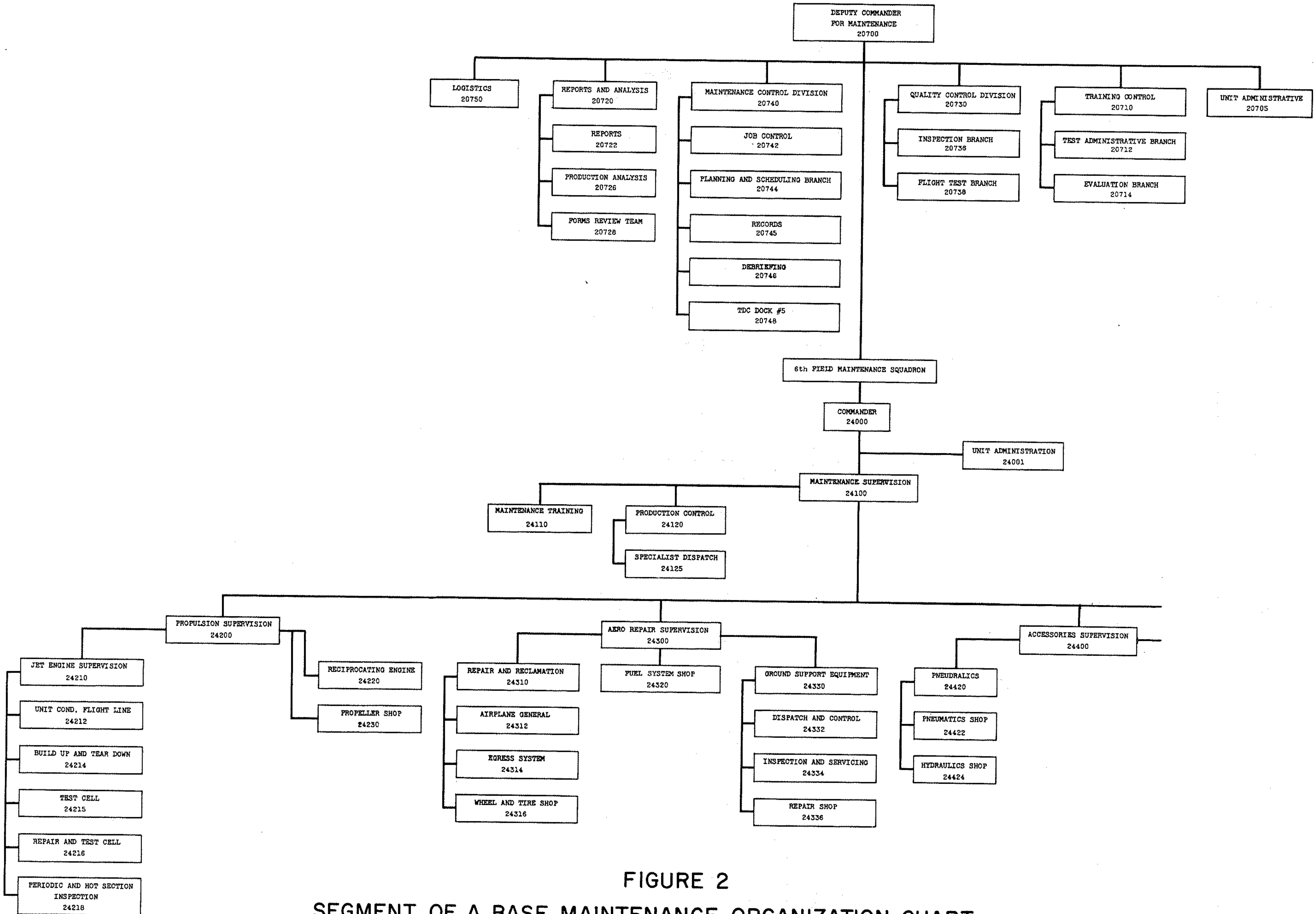
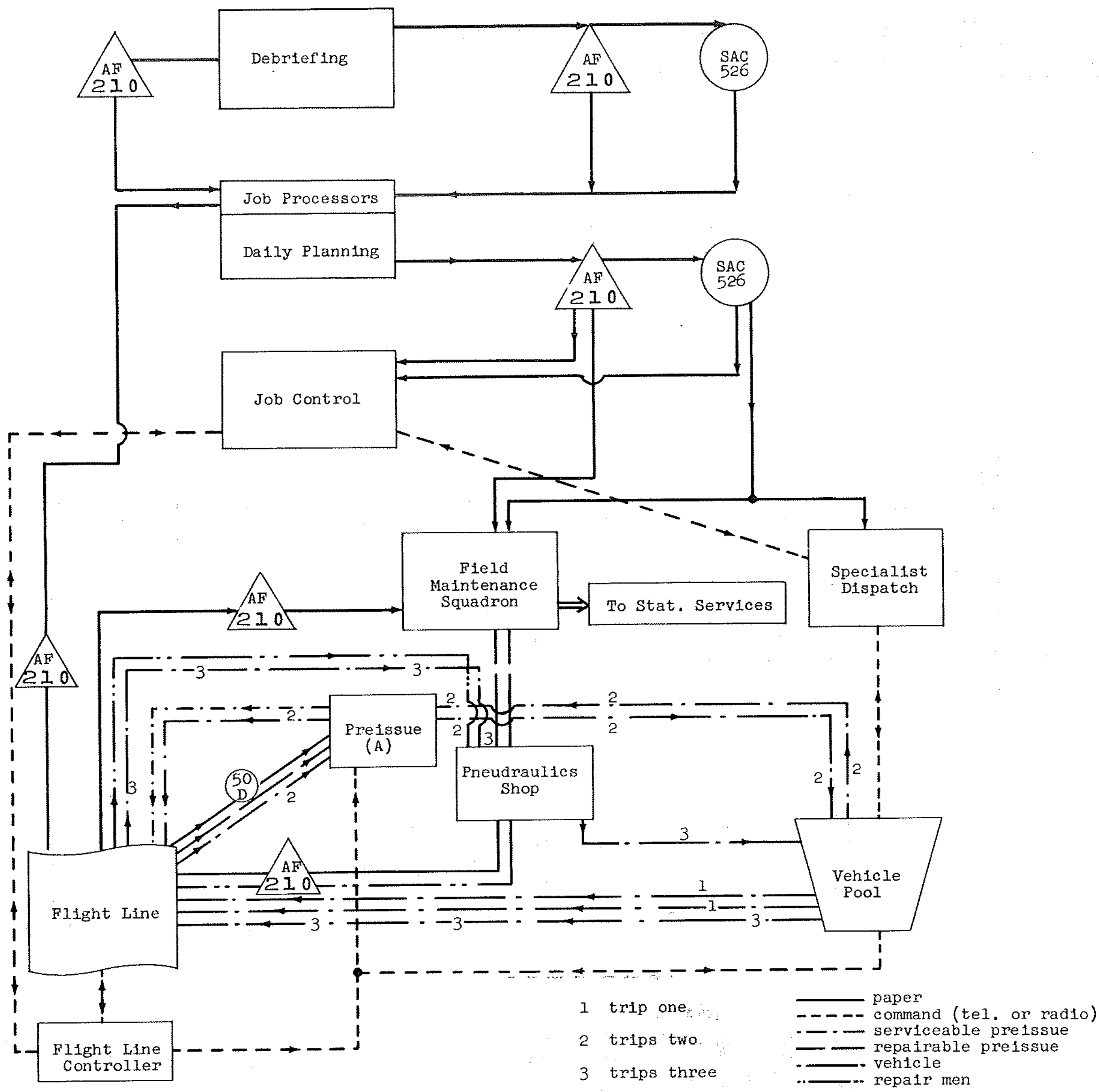


FIGURE 2
SEGMENT OF A BASE MAINTENANCE ORGANIZATION CHART



(A) This repairable preissue generates a shop maintenance cycle.

FIGURE 3

FLOW OF MEN, MATERIALS, AND CONTROL DOCUMENTS

TABLE 1

COST ALLOCATION PRINTOUT

CODE	T	C	L	N	T/N	C/N	L/N
GB211	4.36	$8.59	02.2	01	4.3	8.59	2.2
GB217	5.10	$9.87	02.2	01	5.1	9.87	2.2
GB21	9.46	$18.46	04.4	02	4.7	9.23	2.2
GB2	9.46	$18.46	04.4	02	4.7	9.23	2.2
GB310	23.80	$49.51	08.8	05	4.7	9.90	1.7
GB311	8.37	$14.42	05.4	01	8.3	14.42	5.4
GB313	5.37	$11.51	02.2	01	5.3	11.51	2.2
GB314	10.74	$23.02	04.4	02	5.3	11.51	2.2
GB31	48.28	$98.46	20.8	09	5.3	10.94	2.3
GB350	251.72	$419.65	176.7	299	.8	1.40	.5
GB352	114.70	$192.90	78.8	13	8.8	14.83	6.0
GB35	366.42	$612.55	255.5	312	1.1	1.96	.8
GB360	196.10	$317.30	147.4	373	.5	.85	.3
GB36	196.10	$317.30	147.4	373	.5	.85	.3
GB3	610.80	$1,028.31	423.7	694	.8	1.48	.6

RESULTS OF A TEST-TO-FAILURE PROGRAM ON ELECTRONIC PARTS

Louis M. St. Martin
Staff Engineer
Army Weapon Systems Management Reliability
General Dynamics/Pomona 351850
Pomona, California

17034

Summary

General Dynamics/Pomona as the prime contractor for the MAULER Weapon System is conducting a strong reliability program according to policy established by AOMC. One of the requirements of this policy is that reliability testing of components to failure be conducted in order to determine safety margins. The safety margin is a statistical relationship between the strength of the component and its use environment.

The USAOMC policy was implemented by a MAULER Weapon System Test-to-Failure Plan. This plan established the objectives and scope of the test program, the basis for selection of candidates and test environments, a list of the candidates and environments, uniform test-to-failure language, uniform test method, criteria for judgment of test results, initiation of corrective action on failed items, test reports, and test schedules.

Forty-two tests on twenty-three parts and seven assemblies have been completed; some items were tested in more than a single environment. The environments were high and low temperature, vibration, shock, and acoustic noise. Twenty-six of the tests disclosed adequate safety margins. The other sixteen tests resulted in corrective action ranging from reducing the stress on the item to replacing the item with one of adequate strength.

The lead time gained by this program on the potential problems has been a direct benefit of this program. Of indirect benefit has been the increased confidence the designer has in the items passing the test which allows him to dismiss doubts and concentrate on other unknowns.

The author recommends the use of test-to-failure by designers in selecting and evaluating components, determining the failure modes of parts, materials and assemblies, and identifying "weak links" in a system. It is a discriminating test of subtle changes in design or materials and as such the author considers it useful as a quality control tool or, in non-destructive configurations, a powerful screening test. He recommends it as a prelude to the design of a life test as it provides data on the behavior of the test specimen which eliminates much of the necessary guesswork.

Background

The MAULER Reliability Problem

MAULER is a fast reacting, compact, high accuracy air defense system for forward battle areas. The challenges to the reliability of MAULER are manifold and the U. S. Army expects these challenges to be identified and treated in the early research and development phases during which the tax payer's dollar could buy the maximum of trouble-free life in the field.

The MAULER Reliability Program

Two major MAULER reliability activities are required by Army Ordnance Missile Command; a determination of the environmental stress or design level (Reliability Boundary) which shall be used as the basis for selection or development of parts, sub-assemblies, assemblies and equipments, and an intensive laboratory test-to-failure program of critical parts, sub-assemblies, assemblies and equipments selected for integration into the system.

General Dynamics/Pomona, in agreement with the customer, evolved a broad reliability program which would utilize all the reliability techniques pertinent to the problem commensurate with a balance between the objectives, the AOMC requirements, and the economic resources. This program includes a prediction of the field reliability to identify and correct major weaknesses, an estimate of the field maintenance required to keep the system in operation, establishment of reliability goals to be achieved in design, a comprehensive analysis of the environments and conditions of use, tests of the susceptibility of the elements of the system to failure in these environments and conditions, a continuous review of design paper, guidance in selection and application of parts and materials, a demonstration of the degree to which the reliability objectives have been met in early models, and finally an assessment of reliability in prototype and tactical hardware with appropriate correction of the remaining problems. Coupled with these tasks, there is the reliability engineer's obligation to assist the designer in identifying and eliminating problems as they arise.

The Analysis of Environments

The analysis of environments was divided into three phases. First, a research into all available data on natural environments was made. Data on vibration, shock and noise were obtained during road and field tests of vehicles

similar to the MAULER carrier. The results of these studies were incorporated in the specifications for the various subsystems; radars, computers, power generators, missiles, communications, launchers, etc. Next, the Industrial Team Membe s (Burroughs Corporation, FMC Corporation, General Dynamics/Electronics, General Dynamics/Pomona, and Raytheon Company) performed an analysis in which the external environments of the specifications were combined with the environments generated within the individual subsystem. Finally, the subsystem analyses were combined in an analysis of weapon system environments in which interactions between subsystems were identified. These analyses give reliability and design personnel high visibility into the problems created by the environments and help identify areas of critical weaknesses for use in the reliability predictions and suggest potential corrective actions. The analyses are updated as significant changes in hardware occur or accuracy of environmental data is improved.

With the analyses of subsystem and system environments in hand, the Industrial Team Members were able to compare the capabilities of the parts and assemblies they would be using with the conditions of use, identify those items which appeared to lack the necessary capability, and treat the anticipated problem.

Major Features of the MAULER Test-to-Failure Program

Tests-to-Failure in the MAULER program are performed by the Industrial Team Members. These team members are responsible for selecting item-environment combinations for test, performing tests and analyzing data, making decisions on the acceptability of the tested parts and reporting the results of each test and any ensuing corrective action. The Army Weapon Systems Management Department of General Dynamics/Pomona is responsible for administering the program. The administrative details are contained in a Weapon System Test-to-Failure Plan.

A part is selected for test if it is a high population item, a new or non-standard item, if it has an unknown response to an environment, or a history of failure. A test is defined as failure of all parts of a sample in a single environment. Failure can be any change in part characteristics of interest to the test designer and it is not limited to a permanent change. In the earliest phase of MAULER development, testing was concentrated on piece parts. In later phases increased emphasis is being placed on testing sub-assemblies.

Results of Tests

Table 1 summarizes the results of the forty-two item-environment combinations tested to date, sixteen of which revealed combinations unfavorable to the desired reliability goals. Tests typical of each part type category are discussed below.

Logic Modules

The mode of failure in the tests of Gate-Emitter Follower and Flip Flop modules was cracking of the glass envelope of computer diodes during and after exposure of the encapsulated modules to high temperatures. The defect was corrected by replacing the diode with one of another manufacturer which had not exhibited this mode of failure in other tests-to-failure. No failures occurred during exposure of the modules to four times the end-use level of vibration.

The Buffer module demonstrated an adequate safety margin in high temperature. One sample failed catastrophically when the test signal was not propagated through the circuit. This was attributed to a transistor short at 203.5°C. Six samples failed for degraded performance when signal propagation time exceeded tolerances and one circuit failed when output level drifted outside of the failure criteria for this attribute. The remaining three samples were arbitrarily classed as failures when the test equipment cables failed at 248°C. The effects of high temperature on output level and waveform are shown in Figures 1 and 2.

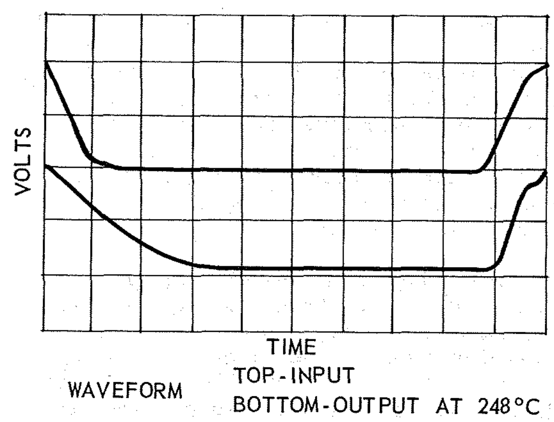


Figure 1

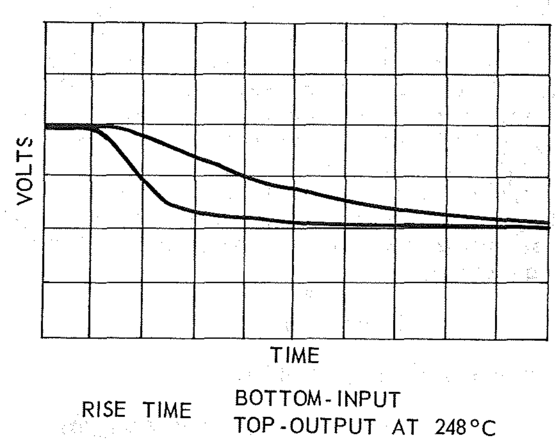


Figure 2

TABLE 1
RESULTS OF MAULER ENGINEERING MODEL PHASE TEST-TO-FAILURE PROGRAM

ITEM	TYPE	SAMPLE SIZE (N)	STRESS	RELIABILITY BOUNDARY	TEST RESULTS X	TEST RESULTS S	SAFETY MARGIN TEST	SAFETY MARGIN REQ'D	DECISION ON ITEM ACCEPT	DECISION ON ITEM REJECT
LOGIC MODULES	2 IN GATE & EMITTER FOLLOWER	10 MODULES; TOTAL N WAS 15 CIRCUITS	HIGH TEMP	74°C	179.2°C	18.3°C	5.8	6.7		X
	TRAILING EDGE FLIP FLOP	5	HIGH TEMP	74°C	177.8°C	19.8°C	5.2	9.8		X
			VIBRATION		NO FAILURES					
	BUFFER	5 MODULES; TOTAL N WAS 10 CIRCUITS	HIGH TEMP	74°C	228.2°C	18.6°C	8.3	7.4	X	
			LOW TEMP	– 54°C	NO FAILURES TO –74°C					
	4 IN GATE & EMITTER	10 MODULES; TOTAL N WAS 15 CIRCUITS	LOW TEMP	– 31.7°C	–71.6°C	4.0°C	9.95	6.8	X	
			VIBRATION		NO FAILURES					
	6 IN GATE & COMP. EMIT. FOLLOWER	2 OF EACH	NOISE	150 DB FOR 250 MS	NO FAILURES AT 160 DB FOR 8.3 MINUTES				X	
	COMPLEMENTARY EMITTER FOLLOWER	1	HIGH TEMP LOW TEMP	72°C – 40°C	NO FAILURES AT 222°C NO FAILURES AT –78°C (LIMIT OF EQUIPMENT)				X	
	SHIFT REGISTER	15	VIBRATION	–	NO FAILURES				X	
		10	LOW TEMP	– 34°C	NO FAILURES				X	
			HIGH TEMP	81°C	103°C	5.2°C	4.0	6.0		X
RELAYS	2 POLE 1/2 X CRYSTAL CAN SIZE (VENDOR NO. 1)	9	VIBRATION	10 G'S 10-2000 CPS	35.5 G'S	11.7 G'S	2.2	7.6		X
	2 POLE 1/2 X CRYSTAL CAN SIZE (VENDOR NO. 2)	9	VIBRATION	10 G'S 10-2000 CPS	35.5 G'S	11.7 G'S	2.2	7.6		X
	2 POLE 1 X CRYSTAL CAN SIZE	9	VIBRATION	10 G'S 10-2000 CPS	40.0 G'S	9.4 G'S	3.2	7.6		X
	4 POLE 2 X CRYSTAL CAN SIZE	9	VIBRATION	10 G'S 10-2000 CPS	–	–	–	–		X
	6 POLE 3 X CRYSTAL CAN SIZE	9	VIBRATION	10 G'S 10-2000 CPS	32.2 G'S	11.3 G'S	2.0	7.6		X
	FUSE-LINK SINGLE OPERATION	15 NO	WATT-M/SEC REQUIRED TO FIRE RELAY	1920 WATT-M/SEC	952.7	97.1	9.9	6.7	X	
		13 NC			840.8	102.5	10.5	6.9	X	
RESISTORS	1/8 WATT CARBON FILM	20	HIGH TEMP	74°C	144°C	5.7°C	12.33	6.4	X	
	1/10 WATT COMPOSITION	20	HIGH TEMP	60°C	187.3°C	9.01°C	14.1	6.4	X	
				100°C			9.7	6.4	X	
	1/2 WATT COMPOSITION	20	HIGH TEMP	60°C	157°C	10.3°C	9.4	6.4	X	
				100°C			5.5	6.4		X
	1/2 WATT COMPOSITION	20	HIGH TEMP	100°C	164.5°C	5.9°C	10.98	6.4	X	
	1/2 WATT CARBON FILM	20	HIGH TEMP	60°C	180.5°C	12.8°C	9.4	6.4	X	
				100°C			6.3	6.4		X
	1 WATT VARIABLE	20	HIGH TEMP	100°C	201°C	11.8°C	8.6	6.4	X	

TABLE 1

RESULTS OF MAULER ENGINEERING MODEL PHASE TEST-TO-FAILURE PROGRAM (CON'T)

ITEM	TYPE	SAMPLE SIZE (N)	STRESS	RELIABILITY BOUNDARY	TEST RESULTS X	S	SAFETY MARGIN TEST	REQ'D	DECISION ON ITEM ACCEPT	REJECT
CAPACITORS	GLASS	20	HIGH TEMP	60°C	185.3°C	11.9°C	10.5	6.4	X	
				100°C			7.2	6.4		
	MICA	20	HIGH TEMP	60°C	121°C	17.45°C	3.5	6.4		X
				100°C			1.2	6.4		X
	SOLID TANTALUM	20	HIGH TEMP	90°C	155°C	17.75°C	3.7	6.4		X
	CERAMIC	20	HIGH TEMP	74°C	216°C	11.4°C	12.5	6.4	X	
DIODES	1N538	40	VIBRATION	3 G'S 41-200 CPS	NO FAILURES TO 25 G'S FROM 5-200 CPS				X	
	1N645	20	HIGH TEMP	74°C	NO FAILURES TO 240°C (TEST CHAMBER LIMIT)				X	
	TYPE A	20	HIGH TEMP	74°C	NO FAILURES TO 260°C (TEST CHAMBER LIMIT)				X	
			VIBRATION	10 G'S PEAK	NO FAILURES TO: 40 G'S FROM 10-142 CPS, 60 G'S FROM 142-2000 CPS				X	
	TYPE B	20	HIGH TEMP	74°C	257°C	23.5°C	7.8	6.4	X	
TRANSISTORS	2N706	12	HIGH TEMP	74°C	NO FAILURES AT 250°C				X	
			VIBRATION	5 G'S < 142 CPS	NO FAILURES TO 25 G'S < 142 CPS				X	
				9 G'S > 142 CPS	NO FAILURES TO 45 G'S > 142 CPS				X	
	2N706	12	HIGH TEMP	74°C	184°C	8.4°C	12.9	7.0	X	
	TYPE C	20	HIGH TEMP	74°C	103°C	23.8°C	1.3	6.4		X
MISC	PRINTED CIRCUIT BOARD CONNECTOR	9	HIGH TEMP	74°C	NO FAILURES AT 250°C				X	
			VIBRATION	5 G'S < 142 CPS	NO FAILURES TO 25 G'S > 142 CPS					
				9 G'S > 142 CPS	NO FAILURES TO 45 G'S > 142 CPS					
	PANEL LAMP	25	SHOCK	36 SHOCKS AT 150G'S	NO FAILURES		–	–	X	

Relays

Table 1 shows three tests on relays on which corrective action has not been determined at the time of preparing this paper. The study referred to in the table is an evaluation of the possibilities of replacing electro-mechanical relays with semi-conductor switches. The trade-offs under consideration here are weight, space, "open-circuit" leakage, cost, and of course, the relative reliabilities of the original relays and the proposed switches.

Resistors

The first test on a half-watt carbon composition resistor showed an inadequate safety margin in high temperature at a reliability boundary of 100°C. The variability was halved and safety margin doubled when the power dissipated in the resistors was cut in half. This is compatible with the recommendations in [1] to derate the part 50% at 100°C.

The high temperature tests on the tenth watt resistor revealed an unexpected mode of failure (see Figure 3). The part demonstrated an average temperature coefficient of approximately one part per million per degree centigrade below 225°C; above this temperature the coefficient reversed and increased to a negative twenty parts per million per degree.

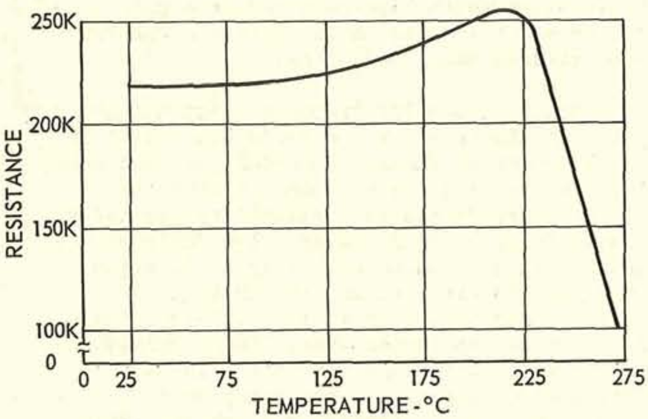


Figure 3

Capacitors

The mica capacitor test revealed a temperature coefficient of capacitance seven times as high as the part specification, MIL-C-5, allows and a safety margin much too inadequate for MAULER's needs. This part was replaced by one with less susceptibility to high temperature. The value of these results was questioned when consideration was given to the high reliability rating given this part in [2]. No comparison of the test results and Ref. [2] can be made because in the above test the failure criterion was one of a transitory performance degradation and in Ref.[2] it is permanent and catastrophic.

Solid tantalum capacitors came under scrutiny in this program. Three failure criteria were used when the capacitors were exposed to high temperature; capacity drift, leakage current less than one milliampere and less than one microampere, at two levels of applied direct voltage. The first test at full rated voltage gave a mean of 155°C and a safety margin of 3.7 above the operating temperature of 90°C, for the one milliampere leakage limit. A small improvement in safety margin was realized in the second test at 80% of rated voltage, but 5.1 was still too small to meet the MAULER definition of an adequate margin. The one microampere leakage safety margin was less than one in both tests. No capacitors failed either test for a capacity change. The Industrial Team Member has elected to use high reliability tantalum capacitors of the "Minuteman" type.

Semi-Conductors

The tests on the Type C transistor demonstrated an inadequate safety margin in high temperature using a minimum current gain of ten as the criterion of failure. An interesting aspect of this test was that the low safety margin resulting from the test was explained by the part vendor on the basis the transistors in the test were "engineering samples" and had not come under "normal quality control", so a repeat test on a sample selected by the vendor was begun. The early failures in the second test were enough to convince the Industrial Team Member the transistor was indeed undesirably unstable and the item was deleted from the MAULER circuits. This step necessitated rather extensive redesign as the replacement device, 2N706, does not strictly replace the Type C.

Conclusions

Test-to-Failure as a Reliability Tool

It is the opinion of General Dynamics/ Pomona the cost of this program will be returned many times over. An example of this ultimate savings to the customer is illustrated by the experience on the Type C transistor. If these tests had not been conducted, the need to replace this item and redesign the circuits to accommodate the more stable 2N706 would not have become apparent until two years later when the subsystem involved entered environmental testing. If the system environmental test sample is small and test conditions abbreviated in the interests of development program economy, as is frequently the case, test-to-failure will identify failures that would occur after delivery when production hardware is exposed to the extremes of end-use conditions. Redesign on the basis of test-to-failure results incorporates a contingency for errors in estimating the end-use conditions and degradation in the strength of the part tested. An example where MAULER test-to-failure

eliminated a problem at subsystem qualification test and end-use is seen in the case of the mica capacitor. 22% of the 200 mica capacitors in a critical subsystem would have failed when subjected to the specification high temperature limit. With a failure percentage this high, the small sample of subsystems currently planned for qualification testing would have disclosed this problem. However, it is doubtful if the qualification test would have revealed anything wrong in the 1300 mica capacitor applications in other subsystems but performance of one MAULER out of five could be degraded when exposed to the high temperature end-use environment. A crash program of failure diagnosis, corrective action and retrofit at the subsystem level would have cost more than the total cost of the entire test-to-failure program on all items at all Industrial Team Members.

A comparison of the variability of part strength with the conditions the part would experience in use is the object of the program and this comparison is being made. Test-to-failure furnishes data on behavior of parts under stress of great value to the designer which is not available by any other means. This information and its application in design improves the chances of delivering reliable hardware. These same data can be useful in reducing cost by replacing unnecessarily strong and expensive parts where adequate strength is available in a lower cost item. Another cost reduction can result from recognizing and eliminating costly environmental protective features which test-to-failure reveals as unnecessary.

Most tests generated the normal distribution of failures assumed by the method, however, instances of distributions other than normal have been noted. Assuming failure of the unfailed items in a sample when a test is terminated prematurely reduces the sample deviation and mean. This effect should be considered in judging the test results.

The timing of these tests is important, if the maximum benefit is to be derived from them. The MAULER tests are being run concurrent with that period when the designer is deciding what parts and assemblies he should use. Having the results available to assist in these decisions has eliminated the cost and delay involved in making the changes after the design begins to freeze up.

Test-to-failure provides the answer to the question, "What happens if the stress on the system is raised?" Taking the test-to-failure results and plugging in the new stress level as a new Reliability Boundary in the calculations gives a quick estimate of the new safety margins. No additional testing is required and the calculation is made in seconds. This stresses the importance of keeping the test data on hand for ready use at any time. General Dynamics/Pomona is doing just this; a summary of the test and its results is included in the MAULER Standard Parts List catalog and a complete file of test reports is available for use. Incidentally, the Industrial Team Members are submitting copies of these reports for inclusion in the Inter-Service Data Exchange Program (IDEP).

<u>Corrective Action</u>

Every test which revealed an incompatibility of part capability with the conditions of use resulted in steps taken to increase the margin between part strength and the critical stress. No problem was dismissed with the excuse that the unsatisfactory item-environment combination was inevitable and MAULER was stuck with it.

<u>Positive Correction</u> - If a part's safety margin was inadequate and stronger parts were available at a low penalty to cost, size, standardization, etc., corrective action consisted of a simple substitution of parts in the design. When the penalties of a part change appeared high, the alternate corrective actions were evaluated with great care. An instance of a decision with a high penalty was the substitution of the 2N706 for the Type C transistor. This action scrapped the design of a large portion of the MAULER computing system. The reliability people involved weighed the problem and its solutions carefully before recommending a change of such import. A situation which also resulted in a major redesign was the decision to replace germanium with silicon semi-conductors.

<u>State-of-the-Art Problems</u> - Not all the problems disclosed by the tests had solutions as clear cut as finding a better part and using it. The tests on relays demonstrated the desired compactness and reliability are not yet available in a single relay. The designer was instructed to examine all relay applications and evaluate each against the criteria of failure used in the vibration test-to-failure and in those instances where the requirements of the application and the part's characteristics were compatible, the relay would be used. In other instances, a slight modification of the environment by isolation or relocation of the relay might suffice. In the remaining cases, if they are few, the price of a larger relay may be within reason. An alternate solution now under consideration is replacing relays of the familiar electromechanical type with semi-conductor switches.

Tantalum capacitors have not submitted readily to simple solutions. The units tested were the penultimate of the reliable types. The decision to replace them with the higher reliability "Minuteman" types was made after a comparison of increased MAULER delivery cost with costs of field failures and repairs showed an appreciable decrease in over-all cost to the Army.

Safety Margins

An unnecessary limitation to the usefulness of this method as a reliability design aid in this program was over-formalization of the test. This was imposed by the prime contractor in establishing it as a major step in demonstrating reliability. Since then both the Army and the MAULER prime contractor have come to realize that an arbitrary safety margin common to all item-environment combinations is not the answer and may result in reliability measures whose cost is out of proportion to the protection needed. This revelation has resulted in elimination of the universal safety margin and the determination of the protection required was left up to the designer's analyses of the problems and their trade-offs, Ref.[4].

In summary, General Dynamics/Pomona has concluded test-to-failure fills a wide gap in our knowledge of item behavior. It:

(a) Provides a measure of item strength in any environment of interest.

(b) Estimates the portion of the population of the item that will fail at any level of the environment.

(c) Reveals modes of non-catastrophic failure at any level of the environment.

(d) Reveals modes of failure at the catastrophic failure level of the environment.

(e) Provides clues to failure mechanisms in assemblies and systems.

(f) Provides failed hardware for analysis to strengthen the part or reduce environmental stress.

(g) Provides knowledge for determining effects of design changes of load, location, environment level, etc.

(h) Identifies abnormal items in a lot when used as a non-destructive screening test.

(i) Is highly sensitive to subtle changes in part material, design, processes and workmanship.

References

1. Application Design Notes (Electronic Components), ASESA 51-4, Armed Services Electro-Standards Agency, Fort Monmouth, New Jersey.

2. Reliability Stress Analysis for Electronic Equipment, RCA Technical Report 59-416-1.

3. Designing Combined Environmental Tests-to-Failure to Yield Effective Reliability Indices, V. L. Grose, Boeing Airplane Co., Test Engineering, May 1959, page 10.

4. ARGMA Procedure for Establishing Practical Safety Margins, 1 May 1961.

Bibliography

1. "Reliability Through Safety Margins", Robert Lusser, U. S. Army Ordnance Missile Command, October 1958.

2. "A Study of Methods for Achieving Reliability of Guided Missiles", Robert Lusser, U. S. Naval Air Missile Test Center Technical Report No. 75, 10 July 1950.

3. "General Specifications for the Safety Margins Required for Guided Missile Components", U. S. Naval Air Missile Test Center Report No. 84, 10 July 1961 (Reproduced by Redstone Arsenal, Huntsville, Alabama)

4. "Testing to Specified Limits versus Testing to Failure", Robert Lusser, 5th Joint Military-Industry Reliability Symposium, Redstone Arsenal, 15-17 October 1958.

5. "Estimating Reliability as a Function of Stress/Strength Data", J. E. Norman, Research and Development Operations, Army Rocket and Guided Missile Agency, Redstone Arsenal, Alabama, November 1961.

6. "Evaluation by Overstress", W. S. Connor, The Research Triangle Institute; Industrial and Engineering Chemistry, Vol. 53, No. 6, June 1961, page 73A-74A.

Appendix A

An Example of the Use of Test-to-Failure as Aid in Design of Other Types of Reliability Tests

The prime contractor used the test-to-failure method in designing an accelerated life test. General Dynamics/Pomona as a result of reliability prediction studies had concluded an improvement of 14% in over-all system reliability would result if a recently developed resistor replaced one of older vintage. The only basis for this conclusion was data generated in tests by the vendor. GD/P wanted to make a quick comparison between the reliabilities of the two resistors. In the interests of efficiency and economy, an estimate of the stress levels which would precipitate resistor failures in a test of reasonable duration was desirable. A test-to-failure was performed which generated failures in a few seconds. The stress (power dissipated in the resistors) was raised at three second intervals until failure (a permanent change of 5% of nominal resistance) had occurred in the entire sample of both resistor types. This developed the data for the curves shown at A_1 and B_1 in Figure 4. A second set of curves, A_2 and B_2 was generated by applying increasing power for six second steps for a total of 0.1 hour.

Fixed stress levels for the accelerated life tests could now be estimated such that the tests would be completed in about ten hours at the lowest stress level on the stronger part. The levels selected were 2.5 and 4 watts. The failure rate of resistor B in this test was approximately one hundred times that of resistor A, as is seen by comparing A_3 with B_3 and A_4 with B_4.

The candidates for the test were selected on the basis of their advertised rating, "1/2 watt". Resistor A is eighteen times the volume of resistor B. This test revealed that failure rate of the parts may be a function of resistor volume. Since resistor A is too large to use without compromising electronic package size, another life test on samples of resistor A of nearly identical volume ("1/8 watt") was performed. A third level of power, 1.5 watts, was run on both the "1/8 watt" resistor A and "1/2 watt" resistor B. The results of the added tests can be evaluated by comparing A_5 with B_3, A_6 with B_4, and A_7 with B_5. The primary conclusion is obvious, even the "1/8 watt" resistor A has a lower failure rate than the "1/2 watt" resistor B. Other conclusions which may be drawn tentatively from this test are: Resistor volume may be a better index of reliability than rating, and wide differences in resistor construction methods may not result in wide differences in reliability.

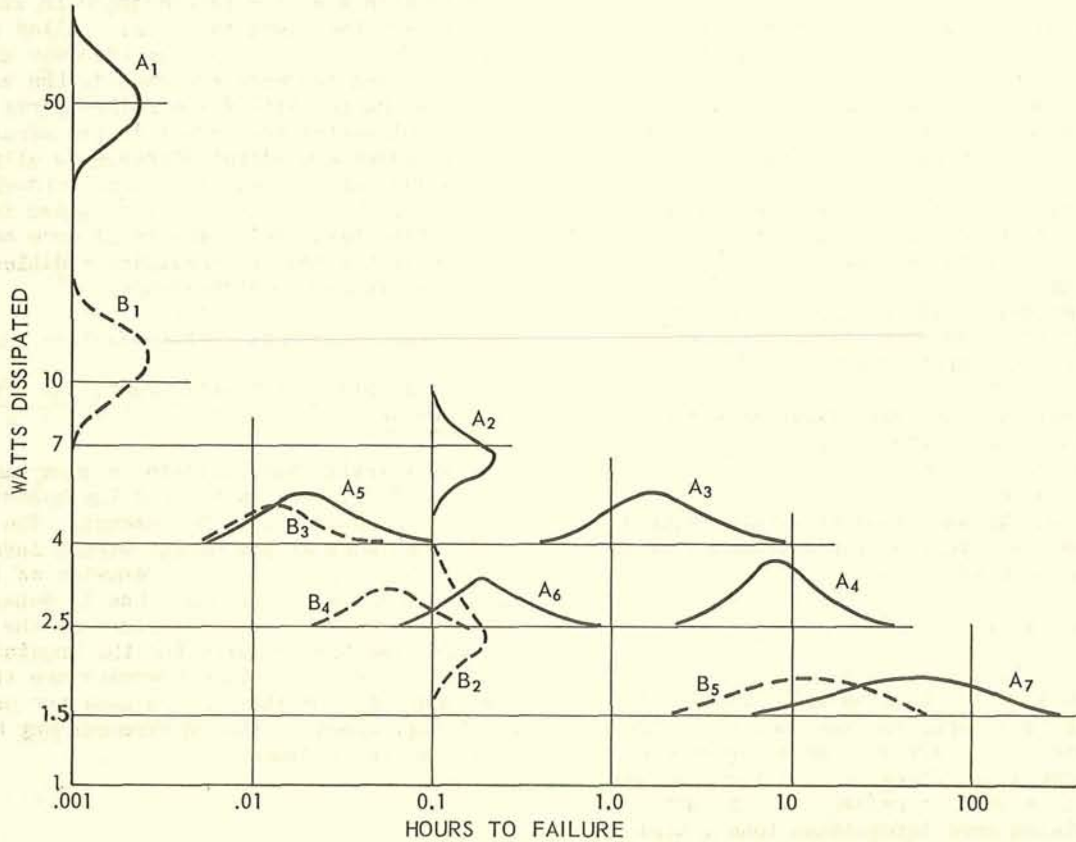


Figure 4

Appendix B

Author's Reflections on Test-to-Failure

Test-to-failure has made a contribution to the MAULER reliability program beyond what would be expected in light of its limited acceptance in the industry. Some of the reasons for rejecting the method advanced during the MAULER program are discussed below.

Test-to-failure has been criticized by some for the reason that it is of little use to estimating part life; the method of applying stress-level-to-failure data to a prediction of time-to-failure has not been established. An item which demonstrates an adequate test-to-failure safety margin may deteriorate rapidly in actual use. This is possible but an item which exhibits an inadequate safety margin at zero time will have a high rate of failure in use. A meaningful life test involves accumulation of several thousand part hours, either with a large sample of parts for a few thousand hours or a small sample for several thousand hours. Test-to-failure on the other hand requires a much smaller sample for tens of hours and it does develop a statistically sound estimate of the proportion of part population that will fail at any level of the applied stress. The information obtained in test-to-failure is of value in designing a life test (see Appendix A).

Another criticism leveled at test-to-failure is it is not as good as a qualification test-to-specified-level because it measures strength in only one environment and is excessively expensive. There is no limitation inherent in test-to-failure against using any and all environments desired, combinations included. (Ref. 3) Like qualification testing, the sample size can be any economically or physically convenient quantity, a little additional time is required to increase the stress and fail all parts in the sample, and the added data analysis can be performed in minutes. What is added is an increase in risk of finding the part unsatisfactory: viz., some parts rejected by this program met the applicable procurement specification. Tests to specified levels such as qualification tests are aimed at getting the parts through without failure, "tests-to-success". Any test which sets out to avoid failure is not a reliability test; reliability testing must generate failures if a statement about the probability of failure is to result. On this premise the author submits test-to-failure is a superior reliability test to the present qualification test.

Test-to-failure critics claim it is not as good as qualification tests-to-specified-level because it is only performed once and therefore gives no protection against a degrading change in parts production. There is no reason for not using test-to-failure to requalify. In fact, because it yields more information than a test-to-specified-level about part strength, it is more sensitive to subtle changes in part design, materials, and processing. A semi-conductor manufacturer interviewed by the author stated he used the method to compare new versions of parts with old to assure continuation or improvement of part strength. This suggests the possibility of using test-to-failure for quick assessment of changes in reliability of "Darnell" and other high reliability parts.

A rather interesting criticism against test-to-failure is that it destroys the sample for later use in experimental hardware. This is true of destructive tests-to-failure; non-destructive tests will leave samples suitable for experimental hardware. The failed parts are useful, particularly if the part demonstrates an inadequate safety margin. In these failed parts reside the clues to improving them, or reducing the critical stress and achieving an adequate margin. Specimens from a test which demonstrated adequate margin should not be arbitrarily discarded either. Examination of these may reveal failure mechanisms which could identify potential problems not anticipated. These failed parts can also disclose failure mechanisms which can result in secondary failures in other parts. An example of this is the negative temperature coefficient above 225°C on the tenth-watt resistor tested in this program. This information will help the designer in protecting parts associated with these resistors from overload. It will also help explain why resistors in a system have dropped in value and provide the clues to a fix. Failed diodes removed from the Gate-Emitter Follower and Flip-Flop modules were returned to the vendor who upon examination of the failed parts was able to pin-point the defect in his manufacturing processes and effect a change to eliminate the failure mechanism. Individual circumstances dictate whether the information gained from a destructive test-to-failure is of more or less value than the cost of providing additional parts for experimental hardware.

The author recommends test-to-failure for use:

As an Aid in Selecting Parts for a New Design

As a design aid, test-to-failure has no equal in furnishing data about the behavior of the item in a critical environment. The item's ability to work at the design stress level and above can be assessed. Its behavior as the failure level is approached, how it behaves in failing, the shape and parameters of the failure distribution are revealed for the inquisitive. And the wonders of failed hardware are there for study; if the item is too weak for use as it stands, clues to its improvement may be found in its remains.

To Evaluate the Effect of Environment Level Changes on Reliability

Once a test-to-failure has been performed, there is no need to run another test to determine the response of the item at a different level of the environment. Compare the distribution of the part failures with the new level and the answer is available. This is not true of tests to specified level; if the new environment level is higher, a new test must be performed.

Use it to Qualify and Requalify Material and Parts

The sensitivity of this test and the information it reveals about the strength of hardware make it a powerful and economic method to establish a desired reliability level and maintain it in production. The quality of some items can be effectively controlled by using non-destructive failure criteria, thus test-to-failure can be used to screen out the weak items in a lot.

Use it as an Aid in Life Test Design

The example given in Appendix A demonstrates the method's usefulness in planning a life test, particularly in selecting the stress levels to be employed in accelerating the test. Life tests for comparing the reliability of two or more similar items are not necessary if comparative tests-to-failure are run. The life of a part is improved by making it stronger or reducing the stress on it and this test will find the answer quicker and at less cost than a comparative life test.

THE HUMAN AS A MISSILE SYSTEM COMPONENT

R. F. Chaillet & A. Steinberg
Army Ordnance Missile Command
Redstone Arsenal, Alabama

The Army Ordnance Missile Command (AOMC) approach to missile system reliability achievement is through strong design control during development. Human engineering is one of the principal controls over design. As the missile system development phase progresses, design weaknesses should be uncovered by design review, laboratory environmental tests, and complementary investigation and analysis prior to field tests of the system. System tests, then, is presumed to be a demonstration of design achievement.

A study was made of approximately 1,000 flight tests of Army missiles at various test sites. These were system tests which are usually conducted under optimal conditions. The weather is ideal, the target position is generally known, and the operator(s) is aware of the firing schedule. Thus, test failures are probably less frequent than might occur in a tactical environment where, in addition to degraded conditions, emotional factors are multiplied. However, due to the lack of realistic tactical situations for testing, we are obliged to use the test results available for information concerning system design achievement. These tests present little data regarding ground support equipment, for the test is principally one of missile achievement. In this context then, identifiable human errors were studied and an analysis of the cause of failure attempted. A word of caution however, due to the paucity of reported data on missile flights, at best, our ability to localize each failure to a specific malfunctioning part or human error is questionable.

Human Engineering and Design

Unfortunately, our system tests have shown us that often the design was inadequate. Design inadequacy is not due to incompetency of design personnel but to their inability to be specialists in all design areas. For example, the designer may be told that his design must operate in a cold environment of -65°F. His concept of the operational environment may not extend beyond the work bench in front of him and the relatively comfortable flow of conditioned air around him. In this aura of job satisfaction, he designs and constructs equipment that <u>he</u> can operate and maintain very effectively. When necessary, he can make all system adjustments with ease. His bare hand fits into each area and, with a minimum of effort, he can replace parts. He is not in any hurry to escape his environment to a warmer, cooler, or safer one as might be the case for a soldier in the field. The designer may reason "these adjustments and repairs can be made so easily that with so little effort, I can miniaturize the equipment to save space" and in so doing, make adjustment of the equipment at cold temperatures impossible. Somewhere in the design process, the interaction between the equipment and the operator becomes lost and our design engineer begins to view his portion of the system as if it were the total system.

It has been stated that "Machines do not operate by themselves". This is extremely important to remember as our systems tend toward automation. Automation does not eliminate the man it simply changes the nature of the task he performs. So constant serious consideration should be given to the human's task as we automate in system design, at least until such time as man himself is completely replaced by machines.

The popular concept of human engineering is that of tinkering with "knobs and dials". Certainly this is a portion of Human Engineering, but only a very small portion. You may have heard the phrase "man-machine relationships" spoken as though it were some witch doctor's mumbo-jumbo, that when uttered, will mystically eliminate your problems. Human engineering is nothing more than an application of the scientific method to systems design to achieve the best feasible assignment of system task responsibilities to the human and/or the equipment. The human engineer wants to study the design, to relate the design to human behavior data, and to recommend changes, if necessary, that will permit his component, the human, to perform effectively. His goal is to educate the design engineer in terms of the capability and limitations of the human component.

Human Engineering provides distinctive gains in system reliability because the completed design will reflect reasonable demands on the human in terms of system operation and maintenance. For example, there are systems in use today that place the guidance and control responsibility squarely on the human operator. This is an unrealistic assignment when one considers the human parameters of response time, eye-hand coordination under stress situations, and the tendency to overcompensate when correcting previous errors, to mention but a few. From a design viewpoint, though, humans are very inexpensively mass produced guidance and control systems requiring no unique production tools.

At AOMC we prefer to see the contractor's Human Engineers in an organizational position to assure acceptance of their design recommendations. In this way, the human engineers can work with all organizational elements on a variety of projects, cross indoctrinating and educating as they work.

Cause of System Failure During Test

Unreliability can be introduced into Missile Systems at the time of manufacture or during field operations. Quality control should detect manufacturing defects, however, we have had situations where the quality of soldered connections went "out of control" and remained undetected until field testing. In this instance, all missiles were recalled by the manufacturer for a secondary review of workmanship. Except for this isolated situation, the human contributions during manufacturing processes relating to failures in systems testing have been difficult to detect. Therefore, they will not be considered in the remainder of this paper. We are not minimizing this aspect. On the contrary, this entire area should be studied thoroughly as a possible means of improving reliability and reducing the number of line rejects in production.

Flight tests that have failed in field operations as a result of human error can be attributed to one of three principal causes:

1. Maintenance errors.

2. Pre-firing adjustment errors.

3. Operator error introduced at or after launch.

The number of readily identifiable human errors in a system testifies to the design inadequacy of that system. Training in system operating procedures, when used as a substitute for effective design, highlights the human errors thereby raising the hue and cry "Pilot Error" and thus absolving the system of any blame.

Types of Guidance

Before analysing the flight data, some knowledge of the types of guidance techniques must be available. With respect to human effects on flight tests, AOMC missile systems may be considered as automatic, semi-automatic, or manual during missile flight. By this criteria, ballistic missiles are considered fully automatic since the course cannot be altered during flight. Hawk, Nike Hercules, and Lacrosse display various degrees of automation. The anti-tank missiles, SS-10, SS-11, and Entac, are manual and the operator is a vital part of the guidance loop during flight. As may be suspected, the manual systems have the highest recorded percent of system failures as a result of human error.

Electronic devices in the semi-automated systems generally replace what would otherwise have been a manual guidance system. Such devices, whether radar, infrared, etc., are complex to construct, adjust, and test. For such semi-automated systems, the major human error contribution to flight failure appears to be introduced during checkout or alignment.

The objective of firing a missile is to destroy a target. All tests that fall short of this objective are graded as failures. Should the missile not contain a warhead, a success is recorded if the miss distance is within the lethal range of the warhead scheduled for use with the missile undergoing tests. In the case of Ground to Air Missiles Circular Probable Error (CPE) in the conventional artillery sense is not considered an adequate criteria for reliability scorekeeping since the problem is a three rather than two dimensional one.

Table 1

Missile System Flight Failures

Human Error	Hawk	Nike Hercules	SS-11
Improper Maintenance	11	5	0
Preflight Maladjustments	13	1	0
Operator Error	2	1	7
Total	26	7	7
All Failures Analyzed	270	303	46
Human Error to All Failures Analyzed	9.6%	2.3%	15.2%

System Data

Hawk

The Hawk is the AOMC system with the largest missile parts population, and therefore, with the greatest missile complexity. It is also the most automated in flight operations, excluding ballistic missiles.

Of the 26 identified human errors causing flight failure, 2 rounds were R&D tests, 7 were Engineering tests, and 17 were Troop firings. Almost every conceivable error occurred within these 26 failures. Some of these errors were:

1. Reversed voltage because of interchanged leads.

2. Complete sub-system not installed.

3. Maladjustments of synchros, potentiometers, and antennae.

4. Switches left in the 'off' position.

5. Plugs and screws not secured.

Another odd problem was where damage resulted in connectors because of heavy probing with test equipment by maintenance personnel.

Nike Hercules

The relatively small number of human generated failures on the Nike Hercules testifies more to our longer experience with the system than to a greater inherent reliability. The Hercules was developed from the Nike Ajax and operator and maintenance functions were carried over in the orderly evolution. Unfortunately, many of the human engineering deficiencies of the Nike Ajax were redesigned into the Hercules system. The 7 denoted failures represent the usual gamet of negligence such as:

1. Safety leads not removed.

2. Switch in 'test' rather than 'operate' position.

3. Disconnected leads.

4. Command destruct activated prematurely.

SS-11

The series of Anti-Tank missiles tested to date use similar guidance techniques. These involved an optical system and require the operator to manually acquire and control the missile after launch. For these systems, failures may be inadvertantly attributed to operator error when actually functional failure may be the malfactor. For example, test results indicate the missile impacted the ground well short of the target. The operator states he was giving an up command at the time. The operator is judged to have been compensating for previously given commands. A recorder attached to the operators control would have permitted a more thorough analysis of the operator's contribution, if any, to the flight failure rather than accepting subjective judgement of evaluating personnel. At any rate, it is apparent, from the results in Table 1, that functional reliability of the system is considerably greater than operator reliability.

SS-11 tests analyzed were those of a particular series conducted at Redstone Arsenal.

System Failure - General

In general, there are human errors contributing to missile failure in every system. On a Lacrosse round, the operator improperly set a computer. On Redeye, fins were inserted backwards, ignition leads were cut improperly, and failure to uncage a gimboled component prevented the possibility of success. The latter type resulted from the inability to perform correctly a simultaneous two hand coordination function. This occurred in an ideal environment.

In the broad sense, every failure might be traced back to the human. In our failure analysis undefined failure causes are presumed to be material deficiencies. Obviously, many of the undefined failures of Hawk and Hercules may be human errors, so our conclusion must be that our ratio of identifiable human errors to total failures is very conservative for these systems.

Conclusions

1. The design should be simple with a minimum of test requirements and a maximum of modular sub-system items that are replaced but not repairable in the field. It is axiomatic that a soldier will test if allowed to and will improvise if possible.

2. The opportunity for human error is greater in the 'prepare to launch' phase of complex and/or automated missile systems as indicated in Table 1.

3. Training should be an adjunct to effective system design not a substitute for it.

In closing, we would like to emphasize the difficulties inherent in obtaining data to substantiate the human error contribution to the various identifiable failure areas mentioned earlier. We feel that a more rigorous analysis of each missile flight failure should be made. This is not an unreasonable recommendation, and if done, would benefit future designs. We have only to witness the detailed reconstruction of each commercial aircraft accident and the resultant improvement in either equipment or procedures to realize that the effort expended would reflect large gains in future systems.

THE ROLE OF HUMAN FACTORS IN

WHITE ROOM MANUFACTURING RELIABILITY

Edward I. Gavurin, Ph. D.
General Electric Company
Missile and Space Vehicle Department
Philadelphia, Pennsylvania

17276

SUMMARY

It is important to recognize that the overall reliability of equipment is not only a function of the components of which it is comprised but also of the individuals who produce it. Consequently, increasing the reliability of the production workers' performance will also increase the reliability of the finished product. This paper has concerned itself both with the role which human performance plays in white room manufacturing reliability and the techniques for optimizing this performance within a controlled environmental work setting. Consideration has been given to the effect of selection, training, motivation and morale, and the special requirements for glove-handed operations upon the reliability of the white room workers.

In general, all of these factors have been found to be inextricably interwoven. Recommendations for increasing human reliability in white room operations were made.

INTRODUCTION

In recent years the use of highly controlled environmental work settings has become more frequent. This is undoubtedly due to the fact that government and industry have become considerably more aware of the role which cleanliness plays in the fabrication of reliable equipment.

If we briefly examine a typical white room specification,[1] we find that it contains special requirements relating to:

1. temperature
2. humidity
3. pressure
4. dust control
5. the interior finish of the walls and ceilings
6. furniture
7. utilities
8. fixtures
9. lighting
10. personnel cleaning chambers
11. dust preventative clothing, etc.

In addition, such a specification also calls out the special regulations and procedures which white room personnel are required to observe. Examples of some of these are as follows:

1. Excessive coughing or sneezing is not permitted.

2. Smoking or eating is prohibited in all work areas.

3. Personal articles normally carried in the pockets such as keys, watches, coins, handkerchiefs, kleenex, cosmetics, etc., are not permitted.

4. Special dust-preventative clothing including boots, caps, and gloves must be worn.

5. Special procedures must be observed in cleaning shoes and utilizing the air shower.

6. Finger nails must be scrubbed and cosmetics removed.

7. Eyeglasses, if worn, must be washed and dried with lint free tissue prior to entering the white room, etc.

This list of white room requirements and regulations is, of course, by no means complete. Nevertheless, it serves to indicate the peculiar nature of the white room environment and the working conditions which prevail within it.

It should be fairly obvious from a review of these requirements that for the uninitiated, this is a strange, unusually restrictive place to work. It is for this reason that special indoctrination programs preparing new employees to meet the demands of this totally unfamiliar setting have been developed wherever white rooms exist.

Unfortunately, management very often naively assumes that the unfamiliarity of the white room situation can be readily overcome by means of these indoctrination sessions alone.

Experience has shown that this assumption is erroneous, although such programs can do much to prepare the new employees for their white room jobs. A major reason for this is the fact that the behavioral requirements of a particular job are different inside the white room than they are outside of it. Consider, for example, the nature of an electronic module assembler's job outside the white room. In this setting, he usually assembles the small parts, dressed in his normal work clothing, with the use of his bare fingers and a number of personalized tools as aids. When he enters the white room, however, he is expected to accomplish the same task wearing his white room uniform, gloves, and deprived of any of the special tools which have already been integrated into a well-developed, smooth and successful operation. By virtue of these seemingly minor changes imposed by the white room environment, we have nevertheless changed the behavioral demands of the job. Glove-handed finger dexterity is different from bare-handed dexterity and the absence of familiar aids makes it necessary for the assembler to change his activity in order to accomplish the same task without them. Unfortunately, the subtleties of such differences makes them difficult to anticipate and their adverse effects on the finished product are often attributed to wrong causes.

The aim of the present paper is therefore to describe techniques and procedures which the writer has employed in studying human factors white room problems and to present the results of these studies along with general recommendations for maximizing human performance in white room settings. The discussion which follows will therefore concern itself with a number of critical factors which singly and combined affect workers' performance. Four factors will be discussed—namely, selection, glove-handed assembly, training, and morale and motivation.

SELECTION OF WHITE ROOM PERSONNEL

Since a white room environment is in many respects alien to anything which most workers are accustomed to, it is only natural to consider the possibility that the standard selection practices, usually employed in choosing production personnel for the conventional production job, are inadequate or inappropriate for the purposes of white room selection. That this is so, has already been alluded to in the introductory section of this paper and, in order not to belabor the point, we will assume that the matter is at least worthy of investigation. Two aspects of selection must be considered in such an investigation. These are skill factors and personality factors. The former refer to those aspects of the worker's behavior which constitute his technical proficiency, while the latter concern his psychological adjustment to his work, his co-workers and his physical surroundings. These two aspects of selection are equally important in choosing individuals who will perform their jobs reliably. It is therefore essential that valid selection criteria be developed for each of them in order to permit us to predict reliable job performance prior to placing a worker on the job.

In a recent study performed by the writer, the following steps were used in developing the skill criteria for white room personnel, working on highly complex electronic communications equipment with a very high reliability requirement.

First, a job analysis was performed on each critical white room job. This involved a complete review of all of the basic tasks of each job. A detailed description of each job reviewed was written, and served as basic data for making tentative determinations of the types of aptitudes necessary for successful work performance.

Second, aptitude tests were administered to each white room employee. More specifically, the General Aptitude Test Battery, developed by the United States Employment Service and consisting of twelve individual tests was administered. These twelve tests measure the following nine distinct aptitudes:

1. general intelligence

2. ability to comprehend the meaning of words

3. ability to perform arithmetic operations quickly and accurately

4. ability to think visually about geometric forms and to comprehend two-dimensional objects

5. ability to perceive pertinent details in objects or in pictorial or graphic material

6. ability to perceive pertinent details in verbal and/or tabular material.

7. ability to coordinate eyes and hands or fingers rapidly and accurately in making precise movements with speed.

8. ability to move the fingers and manipulate small objects with the fingers rapidly and accurately.

9. ability to move the hands easily and skillfully.[2]

This test battery was administered in order to determine the specific combination of aptitudes

(specific battery) predictive of success for each distinct job under investigation. Once such specific test batteries were developed for each white room job, they could be compared with the specific batteries already employed to select workers for similar jobs outside the white room. If these batteries were identical (i.e. consisting of identical aptitudes) then we could deduce that at least the skills necessary for success on these jobs were identical inside and outside of the white room. If the specific batteries were different, however, the new specific batteries developed would serve as selection devices for the white room jobs.

It has been noted above that skill factors represent only one facet of white room selection. The other factor is the personality make-up of the worker. Consequently, the development of suitable selection criteria must also take into account personality traits. The Thurstone Temperament Schedule, a personality test measuring seven distinct personality traits was administered to each white room employee. The traits measured were as follows:

1. Active (A). A person scoring high on this trait usually works and moves rapidly. He is restless whenever he has to be quiet. He likes to be "on the go" and tends to hurry. He usually walks, writes, drives, and works rapidly even when these activities do not demand speed.

2. Vigorous (V). A person with a high score in this trait participates in physical sports, work requiring his hands and the use of tools, and outdoor occupations. This trait indicates an emphasis on physical activity using large muscle groups and great expenditure of energy. This trait is often described as "masculine" but many women and girls will score high in this area.

3. Impulsive (I). High scores in this trait indicate a happy-go-lucky, daredevil, carefree, acting-on-the-spur-of-the-moment disposition. These people make decisions quickly, enjoy competition, and change easily from one task to another. The decision to act or change is quick regardless of whether the person moves slowly or rapidly (Active), or enjoys or dislikes strenuous projects (Vigorous). A person who doggedly "hangs on" when acting or thinking is typically low in this area.

4. Dominant (D). People scoring high on this factor think of themselves as leaders, capable of taking initiative and responsibility. They are not domineering, even though they have leadership ability. They enjoy public speaking, organizing social activities, promoting new projects, and persuading others. They are the ones who would probably take charge of the situation in case of an accident.

5. Stable (E for emotionally stable). Persons who have high scores in this trait usually are cheerful and have an even disposition. They can relax in a noisy room, and they remain calm in a crisis. They claim that they can disregard distractions while working. They are not irritated if interrupted when concentrating, and they do not fret about daily chores. They are not annoyed by leaving a task unfinished or by having to finish it by a deadline.

6. Sociable (S). Persons high in this trait enjoy the company of others, make friends easily, are sympathetic, cooperative, agreeable in their relations with people. Strangers readily tell them about personal troubles.

7. Reflective (R). Persons high in this trait like meditative and reflective thinking. They enjoy theory rather than practice. These people are usually quiet, like to work alone, and enjoy tasks which require accuracy and fine detail. They often take on more than they can realistically accomplish and would rather plan a job than actually carry it out themselves.[3]

The third and final phase of the program for developing selection criteria for white room personnel involved the validation of the aptitude and personality test scores against actual work performance. In other words, by correlating test performance with work performance, using appropriate statistical techniques, we were able to determine which tests were predictive of success for a particular job. To perform such validation studies, however, it was necessary to have a measure of work performance. Two such measures were utilized. One was in the form of objective production records indicating quantities produced, number of items rejected, number of items produced per unit time, etc. The other was in the form of supervisors' ratings consisting of a numerical appraisal of the worker's performance on a number of distinct work performance factors.

Although no attempt will be made in this paper to present the specific test batteries or personality profiles associated with success on the white room jobs studied, a number of general findings are worthy of mention. Perhaps the most significant finding is the fact that the nature of most jobs actually change when they are performed in a white room setting. This was evident both from the job analyses performed, and from the fact that the specific test batteries predictive of success in performing jobs in the white room were different from those predictive of success in performing the same jobs in conventional factory settings. Of special importance in this connection was the data obtained from the job analyses. These clearly revealed the impact which the special white room requirements impose on the jobs performed. For example, the em-

phasis on quality rather than quanitity completely changed the relative importance assigned to such factors as speed, accuracy, visual acuity, manual dexterity, motor coordination, etc. In other words, each job changed as a function of the changes in the skills required, and the degree to which these skills were needed for a particular job. So far as personality factors are concerned, it was found that in general, the individuals best suited for white room work generally obtain scores which ranged as follows on the seven factors of the Thurstone Temperament Schedule:

1. High in (E) Stable

2. Average in (A) Action, (V) Vigorous, (S) Sociable

3. Low in (I) Impulsive, (D) Dominant, (R) Reflective

Individuals whose scores do not fall within these broad ranges would generally find the adjustment difficult and the atmosphere oppressive.

The recommendations for white room selection generated by the study are as follows:

1. Special selection criteria for skill must be developed for choosing white room personnel. This is so since white room procedures materially alter the skill requirements of similar jobs performed outside the white room. The paradigm for developing these skill criteria have been described above. It basically consists of:

a) performing a job analysis of the critical white room functions

b) administering a wide range of aptitude tests to white room incumbents

c) correlating the aptitude test scores against white room performance measures such as production records and supervisors' ratings

d) deriving special aptitude test batteries predictive of success for each of the critical white room jobs

It should be noted that the specific white room aptitude test batteries which the writer derived are not presented here simply because the nature of these jobs will generally be different for each facility. This is so because the specific reliability requirements of each project differs and, as such, are reflected in the manufacturing process, production procedures, and ultimately in the jobs to be performed. The need for a test development program in each case, however, is generated by the fact that high reliability equipment can only be produced by workers whose performance is highly reliable.

2. Even if a worker has the requisite skills to perform reliably in a white room setting, there is no guarantee that he will unless he possesses the necessary personality traits for making a suitable adjustment to this type of environment. For this reason, skill criteria must be supplemented with appropriate personality criteria for valid selection. Here, however, the writer feels that he can be more specific in making recommendations. This is due to the fact that there are strong similarities in the general characteristics of most white rooms regardless of the specific jobs performed therein, which make the requirements for personal adjustment highly similar. Accordingly, the ideal white room personality seems to be an individual who has a high degree of emotional stability, a moderate need for general activity, physical activity and sociability, and a relatively low need to act impulsively, lead others, or engage in meditative or reflective activity. The Thurstone Temperament Schedule, mentioned earlier, appears to be ideally suited to measure these traits especially in view of the fact that its items are couched in language which is well within the reading level of the average white room production worker.

3. A minimum of two years of high school should be required of white room employees since there is a strong emphasis in most cases on understanding written and verbal instructions, both during training and on the job.

4. Some white room jobs are better performed by one sex than the other. Generally, the writer has found females better suited for fine assembly tasks involving small parts, while males seem to perform better on large assemblies.

While it is theoretically true that both sexes can be trained to perform each job equally well, the normal cultural influences provide differential experience for men and women. It is therefore wise to take advantage of these differences in staffing the white room.

SPECIAL PROBLEMS ASSOCIATED WITH GLOVE-HANDED WHITE ROOM ASSEMBLY TASKS

In most white room production facilities which have a requirement to produce very sensitive, highly reliability missile and space equipment, assemblers are required to wear sheer, lightweight gloves while performing their jobs. These gloves are worn in order to reduce the probability of contaminating the equipment with dust particles and organic substances which adhere to or are generated by bare skin. The need for these gloves poses a number of questions, however, for production management. The questions posed are as follows:

1. What effect do gloves have on finger dexterity?

2. In what way is production output affected by the use of gloves?

3. Are gloves with plastic palms and fingers better than all-nylon gloves?

4. Are special aptitude tests or procedures required for measuring glove-handed finger dexterity?

An experiment was therefore designed to provide answers to some of these questions.

The experiment compared the performance of two groups of individuals having identical aptitude for bare-handed finger dexterity on a test for this aptitude where one of the groups took the test with gloves and the other without them. Consequently, the difference in performance of the groups if any, could be attributed only to the effect of wearing gloves.

The results of the experiment clearly indicated a significant loss in finger dexterity and a consequent decrease in output when gloves were used. Furthermore there was a predicted loss of 30% in output for tasks of an assembly nature.

An experiment identical to the one described above but comparing all-nylon gloves with gloves having plastic palms and fingers was also performed. The results of this experiment showed that the plastic material does not facilitate finger dexterity and is in no way superior to 60 denier nylon.

This study therefore leads to the following recommendations:

1. Since even sheer, lightweight gloves significantly reduce finger dexterity, a very careful analysis should be made to determine whether or not their use by white room personnel is absolutely essential for the purpose of reliability. If the decision to use gloves is made, a decrement in the output by assemblers is to be expected.

2. Although there is no significant difference between all-nylon gloves and gloves with plastic palms and fingers, the former type of glove is preferred because it is easier to launder and does not peel or disintegrate as do the plastic ones.

3. Since a strong aptitude for glove-handed finger dexterity is essential in white rooms where wearing gloves is a requirement, the conventional finger dexterity tests used for selection purposes should be administered with the testee wearing gloves. This will provide a more direct measure of aptitude for glove-handed activities.

TRAINING WHITE ROOM PERSONNEL

It has already been pointed out elsewhere that white room management often naively assumes that most of the problems inherent in working in a white room environment can be solved in a number of training sessions. The preceding discussion, however, should serve to emphasize the fact that some individuals, regardless of training, would not qualify for white room work by reason of aptitude, personality, or both. Training should therefore be thought of as useful in preparing the qualified worker for his job in the white room rather than for qualifying an unqualified individual. In other words, training cannot serve as a substitute for a good screening and selection program.

It is only after suitable selection criteria have been used to choose the future white room occupants that a sound training program can be developed. Broadly speaking, such a program, to be effective, should consist of two phases--namely orientation training and technical training. Orientation training should provide:

1. A thorough explanation of the special rules, regulations, and procedures each worker is required to follow and,

2. the rationale for requiring strict adherence to these regulations.

The importance of this phase of white room training cannot be overemphasized because it provides the very basis for each worker's future attitude toward conforming both to apparently rigid standards of behavior and to a strange, unfamiliar physical setting. Consequently, it is only by providing him with a clear understanding of the reasons for these standards and their implications for reliability that he can develop positive attitude toward strict adherence to white room procedure.

Technical training, on the other hand, should be primarily concerned with teaching each white room employee the specific technical skills and knowledge which he will need to perform his job adequately. Emphasis should be given during this phase of training to those aspects of the job which are made unique due to the special white room requirements imposed upon them. Here again, every opportunity should be taken to provide the worker with the rationale for employing the special techniques and procedures which he will be required to adopt. Such explanations are essential if white room personnel are to develop a genuine willingness to relinquish old, familiar work habits for unfamiliar, new ones.

Ideally, training should take place in an environment as nearly similar as possible to the one in which the actual work will be performed. Simulating the white room conditions during training is therefore of special importance in effecting a suitable transition

from training to the real work situation. Such simulation can, of course, be easily accomplished if a special area of the white room is set aside for training purposes only, and if the trainees are required to dress and behave according to white room procedure. Where the aim of training is to teach the trainee to use special tools or to use a tool in a special way, the tools and the units upon which they are to be used should, if possible, be identical with those to be found on the job.

It should be noted that on-the-job training is not recommended as a part of white room training since this technique permits the worker to learn his job on equipment which is being produced for operational use. Such procedure is antithetical to high reliability and should be avoided. Instead, formal training, under simulated conditions, should be employed to bring each worker to the point where he can take his place as a reliable contributor to the manufacturing process.

Since it is not always obvious, it is necessary to point out that training not only has an effect upon the reliability of human performance but also upon conditions of morale and motivation. The reason for this becomes clear when we consider the fact that a worker who is insufficiently prepared for his job cannot hold a very favorable attitude toward his work or his employer. In fact, because he recognizes this deprivation, he is very likely to resent management for failing to provide him with the necessary wherewithal to understand and perform his job to the best of his capacity. As a consequence, he is often prone not to put forth his best effort.

A sound training program is therefore essential to human reliability since it has a profound effect both upon worker skills and attitudes.

WHITE ROOM MORALE AND MOTIVATION

The level of white room morale and motivation is a function of so many factors that it is often amusing to find a superficial attempt to control it by means of "pep talks", newsletters, posters, special badges, and bulletin boards. While such techniques can be beneficial, they are inadequate to materially affect the basic psychology of the white room workers. Much more influential in this respect are the selection and training programs which, if adequate, go a long way toward eliminating the white room "misfit" and his demoralizing effect upon those around him.

To best describe the complexity of factors which contribute to conditions of poor morale and motivation, a specific example will be cited from the author's experience as a white room consultant. Consider for example the following complaints made to the writer by male assembly workers scheduled for white room employment, whose morale and motivation were at an extremely low ebb in anticipation of their new assignment. They complained that:

1. Dressing and undressing was a nuisance and that the procedure was extremely cumbersome.

2. Adherence to the strict procedures was too much of a strain.

3. The nature of the work was tedious and monotonous.

4. The chances for advancement were either absent or extremely limited.

5. The pay scale did not seem to be commensurate with the special work requirements imposed by the facility.

6. The requirement to eat lunch in a special area within the white room itself would generate a feeling of being in captivity.

7. The sterile condition of the white room was a health hazard.

8. The protective hood would cause the hair to fall out.

9. The restrictions upon mobility within the white room were too confining.

10. The requirement to work with gloves made the job more difficult.

11. The prohibition against bringing personal tools into the white room increased the difficulty of the job.

12. The extreme lighting conditions caused eyestrain.

A careful analysis of the situation revealed that these individuals had not been chosen for their jobs on the basis of valid selection criteria. As a matter of fact, high intelligence and strong ambition were the principal criteria used for selection. That these standards were inappropriate can be gleamed from the workers' concern with the monotony of the work, the limited chances for advancement, and the desire for higher pay.

The situation was further complicated by an inadequate training program which failed to provide the men with a suitable rationale for the special white room procedures. This partially accounts for their unaccepting attitude toward the requirements for special white room clothing, the use of gloves, the prohibition against using personal tools, and the strictness of white room regulations.

It will be noted that some concern was expressed with respect to health factors. Here again, a good indoctrination program could have helped dissipate much of the fears associated with excessively sterile white room conditions, falling hair, and eyestrain.

The requirement to eat a lunch in a special area within the white room itself was an unnecessary restriction. Although this requirement is not uncommon, it could not be easily justified to the workers on the basis of reliability. Consequently, the feeling of being a "captive employee" had some basis in fact, with the result that a good deal of resentment was generated because of it.

During the course of the analysis it was discovered that one of the employees possessed a morbid fear of enclosed places (claustrophobia). This individual, obviously unsuited for white room employment, may have conveyed his fear to others around him. Perhaps this accounts for the unusual preoccupation of a number of employes with the confining nature of the work environment.

If we review the factors which contributed to poor morale and motivation in our example, we find the following:

1. The use of inappropriate selection criteria.

2. The failure of the training program to properly indoctrinate white room trainees.

3. The placement of an undesirable restriction on employee mobility during the lunch hour.

4. The failure to screen applicants for emotional disturbances which are detrimental to effective white room performance.

Because it is typical, the specific example cited in this section has been used to illustrate the principal determinants of white room morale and motivation. It will therefore serve to concretize the general recommendations which follow:

1. Valid selection criteria and effective training are critical to the development and maintenance of favorable morale and motivation conditions. Their importance has already been fully discussed.

2. All restrictions on human activity or mobility should be avoided unless they are absolutely necessary for reliability. Unless this principle is followed, morale and motivation will suffer due to a build-up of resentment against the unreasonable encroachment on personal freedom.

3. Techniques and procedures should be developed for reducing the monotony produced by working continuously in a homogeneous environment. One such technique would be to permit white room employees to eat lunch outside the white room.

4. All persons considered for white room work work should be screened by the plant physician to insure the absence of severe emotional problems. Especially harmful to white room morale are individuals who possess strong tendencies toward claustrophobia (fear of enclosed or confined places) and hypochondria (preoccupation with health). The personality tests used during selection should also serve to eliminate emotionally unstable applicants.

In conclusion, the writer would like to point out that he has dealt in this section with factors which he considers to be intrinsic to morale and motivation. If these are optimized there may be very little need to rely on anything else.

REFERENCES

1. USAF Technical Manual T. O. 00-25-203 Standard Functional Criteria for Design and Operation of Clean Rooms, March 1961.

2. Guide to the Use of General Aptitude Test Battery, Section III: Development, United States Department of Labor, Bureau of Employment Security, July 1958.

3. Examiner's Manual for the Thurstone Temperament Schedule, 2nd Edition.

RESOURCES TO SUPPORT A MAN-MACHINE SYSTEM

E. W. Pickrel, Ph.D.
Life Sciences Section
Missiles and Space Systems
Douglas Aircraft Company, Inc.
Santa Monica, California

W. W. Haythorn, Ph.D.
Rand Corporation
Santa Monica, California

17277

SUMMARY

This paper describes a procedure for estimating direct maintenance personnel requirements. A model is presented for gathering information. A sample problem is used to describe manipulation of the information to derive a manning document.

INTRODUCTION

Needs for early support requirement estimates are well known. Personnel plans must be made well in advance of weapon system acquisition to get the necessary budget approval; develop and construct training procedures, equipment and facilities; select, recruit and train personnel; and determine the requirements for and construct housing and other personnel facilities. Some initial estimates of total manning numbers generally must be made at least three or more years before system acquisition, and the additional details of skill types and levels at least two years in advance.

An objective stated explicitly in many personnel requirement estimates growing out of GORs, SORs, manufacturer's proposals and the like, is to minimize personnel requirements. This objective is considered wrong. The objective advanced here is to increase an effectiveness-to-cost ratio.

Assumptions

A decentralized missile force with a central maintenance area will be used as an example when illustrating the effectiveness-to-cost ratio, but a subtender with subs is equally appropriate. A series of assumptions are made.

a. Launch capability can be increased by either placing more maintenance capability at the origin of demands (buying more maintenance capability) or buying more missiles.

b. Centralization of resources so they serve multiple locations provides greater opportunity for resource utilization but the travel time reduces weapon responsiveness and increases missile downtime.

c. Missile system are quick reaction weapons. Maintenance capability at a central support area is useless after the start of hostilities.

d. Resources may be ranked by potential rate of call, as a guidance technician may have a higher expected rate of call than an air-frame repairman. In this case, the value of each additional man placed at the origin of requirements diminishes with each successive assignment. Eventually the manning of an additional position, and its potential return in launch capability, costs more than a comparable return from purchase of another missile. At this point the cost of manning an additional position is considered greater than its potential return through increased launch capability. Purchase of more missiles becomes the efficient approach to increase in launch capability.

Procedure

All resources are tentatively located at the central area and made available through specialist dispatch to the source of demands. To compute the expected alert levels with non-manned launch complexes, the expected demands are multiplied by the times required to meet them plus the travel time from the central maintenance area, and this product is subtracted from the total missile time available. This residual number, divided by the total missile time available, yields the percentage of missiles normally on alert if the number of

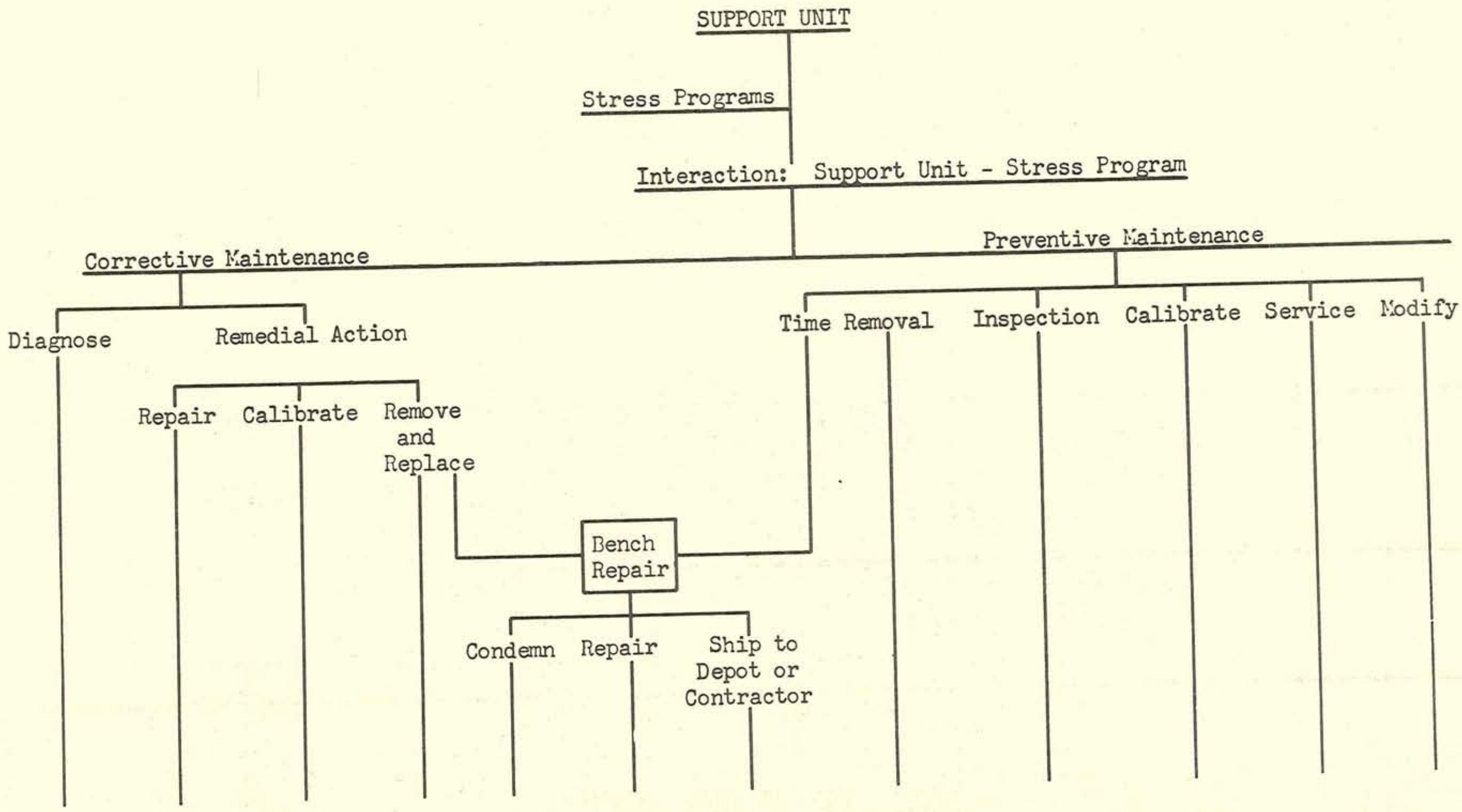
TABLE 1

LIFE OF A SYSTEM

Phase	Time in Years								
	0	1	2	3	4	5	6	7	8
Need	A								
Ideas		B							
Mockup			C						
Sample system				D					
Operational system					E	E	E	E	
Outmoded system									F

TABLE 2

SUPPORT RESOURCE INFORMATION MODEL



of maintenance men assigned to the launch complex is zero. (This is convertable to expected launch success by multiplying the alert percentage by missile launch reliability. For example, if expected alert is 70% and launch reliability is 50%, expected launch success is 35%.)

The first position filled at the source of demands is that which makes the greatest contribution to launch capability (the criterion). The cost of manning this position, including the requirements for crew rotation, equipment, and additional facilities, is compared to the cost of an equivalent increase through purchase of another missile. When manning the position is a more efficient approach, the assignment is accomplished.

The residual of tasks is reaggregated to form new positions and that position at the source of demands which would make the second greatest contribution is filled. The cost of manning this position is compared to the cost of an equivalent increase through purchase of another missile. When manning the position is a more efficient approach, the assignment is accomplished. The iteration is continued, manning positions at the source of demands until the cost of an equivalent increase through purchase of another missile is the more efficient approach. This approach to resource allocation, this trade-off between cost of a man and his contribution to launch capability, is an insurance allocation procedure. It in no way reflects the common objectives of minimizing manpower requirements or maximizing manpower utilization.

Maintenance manning for the central support area is determined by first estimating total workload expected for the organization and assigning as much of it as possible to insurance resources already allocated at the source of demands. Then the additional men required to accomplish the residual workload are assigned to the centralized maintenance area. To illustrate the procedure we now would like to work through an example problem with you.

THE PROBLEM

How many of what kinds of resources are needed where and when to support a missile or a man-machine system? This is an example support allocation problem. Look at Table 1. This presents a time phasing of the life of a system. Imagine yourself at point A. A word picture of need for a new system has been presented in such nebulous terms as "We need a missile type of weapon." The ideas at point B, (we need an ICBM, perhaps several per target), of a system to meet these needs provide a highly abstract picture of system composition. Imagine yourself being asked, at this point in system development, to specify the resources, the personnel, spare parts, and equipment for support of the system.

Imagine yourself at point D, and being asked the same questions. Now a sample system is available. You can be far more accurate in your description of support needs if you accumulate the right kinds of information.

This paper describes an information model for use at the point D stage when estimating resources to support a system. The inputs can be identified within exhibits and requirements present in today's Air Force contracting structure.

Resource requirements will be computed for a sample problem. The model assumes availability of information from earlier stages such as A, B, and C in Table 1. Information in the model has been generalized for application to these other stages of system life.

AN INFORMATION MODEL

Table 2 is a schematic illustration of the information model or basic data package. The numbers and location of resources to support a system can be determined by analyzing the characteristics of the support unit. The support unit is a lowest common denominator for support at a given location. Call this one a stable platform in the guidance system.

Support Unit

You must identify support requirements at the module, component, or unit level that support will occur. This level of detail will vary with location; limiters will be introduced later.

Describe the system-oriented, functional characteristics of the unit. If its uncorrrected failure would abort the missile, there is need for immediate corrective maintenance. This kind of demand imposes a high time stress on the resource structure. Identify these critical-task characteristics. How frequently will the demands for resources arise?

Kinds of Tasks Imposed by Support Units

Identify resource requirements imposed by each kind of task. The information model shows task

TABLE 3

Support Unit	Critical	Corrective Maintenance Tasks					Preventive Maintenance Tasks			
		Diagnosis		Remedial Action						
		Mech.	Man.	Remove	Repair	Cal.	Inspec.	Servc.	Cal.	Time Remove
1	+*	0	+*	+*	0	+*	+	0	0	+
2	0	+	0	+	0	0	+	+	0	0
3	+*	0	+*	+*	0	0	0	+	0	0
4	+*	+*	0	+*	0	0	+	+	0	0
5	0	0	+	+	0	0	+	0	0	+
N										

Code: + Yes
0 No

TABLE 4

CORRECTIVE MAINTENANCE TASKS

Support Unit	Expected Frequency of Failure	Diagnosis		Remedial Action		
		Manual	Mech.	Remove	Repair	Calib.
1	.002	027[1]:2[2]		215:2		027:3
3	.0022		X	045:5	027:3	
4	.0002	027:2		215:2	045:3	027:5

[1] Kind of Resource Designator. Analogous to an AFSC.

[2] Time to accomplish task. Two 15-minute periods in the example.

TABLE 5

RESOURCE TABULATION

Support	Expected Frequency of Failure	027				045				215			
		Diag	Remove	Repair	Cal	Diag	Remove	Repair	Cal	Diag	Remove	Repair	Cal
1	.002	.002			.002							.002	
3	.0022			.0022									
4	.0002	.0002									.0002		
9	.0046			.0046									
17	.0003							.0003					.0003
28	.0031				.0031								
32	.0009						.0009			.0009			
67	.0025												
92	.0036												
		$\Sigma P = .0166$ $\Sigma N = 7$				$\Sigma P = .0012$ $\Sigma N = 2$				$\Sigma P = .0034$ $\Sigma N = 4$			

separation into corrective (malfunction-generated) and preventive maintenance tasks.

Preventive Maintenance. The preventive maintenance tasks generally are not pursued during a battle. The time when resources will meet these demands can be controlled by management without a change in missile readiness, without an additional loss in missile alert time. Location of resources to meet these requirements is determined by workload, a resource utilization criterion. The category includes inspection, a symptom-seeking act frequently accomplished for a group of support units at a given moment, scheduled calibration or periodic alignment to desired standards, a servicing cluster which includes cleaning and lubrication, and scheduled removal of items for overhaul or condemnation.

Corrective Maintenance. The time that malfunctions will occur is generally not controllable by management. The result of malfunctions is a loss in missile alert, missile readiness. Identify resources and time required for corrective maintenance of the support unit. Mechanical diagnostic equipment isolates malfunctions in some support units. Identify the manual assists that are required. Identify the appropriate corrective action and resources necessary. The support unit per se may be removed and replaced at the using location or it may be an integral part of a higher assembly. When within-unit repair is appropriate, identify the environmental and resource requirements. Calibration or alignment following the corrective action also requires resources for a given length of time. Table 3 is the same model in tabular form, and presents another important consideration:

Some support units are critical; correction of malfunctions in these support units would increase the number of missiles launched. Failure of support units 1, 3 or 4 would cause an abort of the missile. Their corrective maintenance tasks are marked with asterisks. Resources to accomplish these critical tasks which would increase the number of missiles launched in time of crisis, are described with greater detail in Table 4. If support unit number 1 malfunctions, a specialist 027 is needed for 2 units of time to isolate the fault. The 02 code represents an engine mechanic; the 7 is his skill level. The time units are 15-minute periods in this problem. Specialist 215 spends 30 minutes in removing and replacing the malfunctioning unit. An 027 spends 45 minutes realigning the system. The use of different specialists in support of a single unit directs attention to possible use of the model as a carrier of task data and later aggregating it into positions. The Expected Frequency of Failure column lists the number of times this unit is expected to fail and generate requirements for each of these tasks. To summarize, the table describes: (a) expected frequency each support unit fails during a launch program, (b) kind of action necessary, (c) kind of resource to perform it, and (d) time necessary to accomplish the task. What resources are needed to support these possible demands? The resource information is fragmented by support unit and needs aggregation by kind of resource.

Kinds of Resources Required to Accomplish Tasks

Table 5 presents a re-sorting and aggregation by kind of resource. All tasks in the launch criterion category to be accomplished by a specialist kind 027 are listed here. Their sum is presented at the base of the column. Only seven tasks may call for the services of specialist 027. The chance of call during this kind of program, launch preparation, is .0166. Most of the time these resources would be idle. Yet there is a chance of two or more calls for a specialist to occur simultaneously.

Resources are assigned tentatively for these critical tasks which, by definition, they can meet. These launch critical or time-stress tasks are the criteria for placing resources at the source of demands. A corollary problem is accomplishment of non-critical day-to-day tasks. These are assigned until either the resources' available time or the task pool is exhausted.

AN APPLICATION

This model was used in a simulated ICBM setting in the RAND Logistics Systems Laboratory to: (a) yield resource allocation (man and support equipment), (b) estimate the degree they were utilized, and (c) show the relation between increasing launch crew size and operational alert and launch success. We plan to use the model in estimating maintenance requirements for Skybolt, a Douglas ALBM for SAC and British Aircraft.

ON THE APPLICATION OF LINEAR PROGRAMMING TECHNIQUES TO HUMAN FACTORS IN SPACE PROGRAMS

Paul A. Young
Sperry Utah Company
Salt Lake City, Utah

17272 abstract

This paper presents a mathematical model which provides optional crew task scheduling. The model employs linear programming techniques to define an objective function to be optimized based upon individual task proficiencies. A discussion of the definition and evaluation of proficiency indices preceeds the presentation of the assignment model. The methods used to solve the proposed model are not discussed because they are felt to be beyond the scope of this paper.

Introduction

The functional representation of the probability of mission success, or reliability of a space vehicle is defined in terms of two implicit reliability functions: (1) the reliability of the equipment and (2) the reliability or proficiency of man. In general these two functions are not independent, but are in turn, functions of each other. Estimates of equipment reliability can be made through the use of testing procedures on the equipment and statistical models to evaluate the data from the tests. The evaluation of human proficiencies can be made in much the same way. Testing procedures consistant with objectives can be devised and statistical models consistant with the tests applied.

Once these reliabilities or proficiencies have been established it is possible to optimize the reliability of the mission. One aspect of this optimization is to optimize crew selection, scheduling, and task assignment.

Proficiency Indices

Definition of Proficiency Indices

The first step in optimizing human proficiency is the assignment of a proficiency index for each crew candidate for each expected task. The proficiency index is defined as a number C_{ij} which is a measure of the ith man's capability in the jth task. This number would be assigned according to the results of specific tests performed.

The processes involved in the testing require certain observations to be made according to some statistical model and that the data be reduced to provide summary statements appropriate to the investigation. The results of such data often conform to one or two distinct but related types: those pertaining to the differences and those pertaining to the consistancies between variables. The form of the statistics is generally the ratio of two variance estimates, one pertaining to the controlled variation in the tests and the other to the uncontrolled, or sampling, errors. Two statistics which are commonly used in connection with these variance estimates are Snedecor's test-statistic (F) and the coefficient of interclass correlation (R). Each of these statistics is used to answer a different question: F is related to questions of difference while R is related to questions of consistency.

Evaluation of Proficiency Indices

Pursuing this reasoning in more detail, the analysis of variance model for a double or two-way classification is shown below. Suppose the scores for individuals are classified into A groups on the basis of one characteristic and into B groups on the basis of another. Three component-of-variance models are considered: components of variance model (both classifications A and B involve sampling from a normal population), fixed components model (both classifications A and B involve no sampling), and mixed model (classification A involves sampling while classification B involves no sampling).

	1	2	3	j	A
1	x_{11}	x_{12}	x_{13}	x_{1j}	x_{1A}
2	x_{21}	x_{22}	x_{23}	x_{2j}	x_{2A}
i	x_{i1}	x_{i2}	x_{i3}	x_{ij}	x_{iA}
B	x_{B1}	x_{B2}	x_{B3}	x_{Bj}	x_{BA}

Each model requires the same breakdown of the sum of squares and degrees of freedom, giving the same variance estimates. The fundamental differences between the analyses of the models is in the choice of the proper variance estimate to be used with the F statistic. It is important to note that the choice of one crew member in preference to another reduces to the same kind of problem in the analysis of variance as the choice of one transistor in preference to another. If the analysis of variance model has three classifications instead of two then similar techniques may be used. For example, if there is no interaction, the model becomes that of the Latin Square.

One essential difference that exists between the physical and the behavioral sciences (namely, the question of level of measurement)

makes it necessary to extend the evaluation techniques for the human factors area. Many measurements, especially in personality studies do not reach the level that is necessary in order to justify the use of the F statistic. Members are arranged only in terms of the order of magnitude of an attribute and in some cases in groups without regard to order within the group. In either case, the analysis of variance techniques based upon the F statistic cannot be used. For such studies, use can be made of non-parametric tests such as the chi-square or Kolmogorov-Smirnov distributions. Although these tests are not as sensitive as the parametric ones, they will serve as a satisfactory basis in many cases for detecting differences among members.

Based upon the differences shown in the models, each crew candidate can then be assigned a proficiency index for each task. This index will reflect his capability in that task and his standing with respect to the other candidates performances. Using these indices the problem is to optimize crew selection and assignment so as to optimize the probability of mission success.

Linear Programming Model

The General Model

Linear programming could be defined as a methodology for optimizing a given linear function in terms of given linear constraints, and the variables in the function to be optimized are usually constrained to be non-negative. Consider the system of m linear equations in k unknowns

$$\begin{array}{l} a_{11} x_1 + a_{12} x_2 + \dots + a_{1k} x_k = b_1 \\ a_{21} x_1 + a_{22} x_2 + \dots + a_{2k} x_k = b_2 \\ \quad \cdot \qquad \cdot \qquad\qquad \cdot \qquad \cdot \\ \quad \cdot \qquad \cdot \qquad\qquad \cdot \qquad \cdot \\ \quad \cdot \qquad \cdot \qquad\qquad \cdot \qquad \cdot \\ a_{m1} x_1 + a_{m2} x_2 + \dots + a_{mk} x_k = b_m \end{array} \tag{1}$$

where $x_1, x_2, \dots, x_k$ are unknown and the other quantities are constants. Suppose the equations are consistant but not sufficient to determine the x_i uniquely. This indeterminacy will occur if $k > m$, if $k = m$ and the system is linearly dependent; or if $k < m$ the indeterminacy may also exist. If the additional conditions

$$x_i \geq 0 \; ; \quad i = 1, 2, \dots, k \tag{2}$$

$$c_1 x_1 + c_2 x_2 + \dots + c_k x_k = \text{minimum} \tag{3}$$

are imposed, where $c_1, c_2, \dots, c_k$ are given constants, then the problem is to select, out of the infinite number of solutions of the system of linear equations (1), the solution which contains only non-negitive variables and for which the linear form (3) is an extreme.

The general linear programming problem shown above is given in the standard form where all the constraint conditions are stated as equations, and the variables are required to be non-negative. This need not be the case generally. Linear programming applies equally well to problems where the constraints are inequalities or a mixture of equations and inequalities, and some of the variables can be negative.

If a constraint is defined as a less-than condition so that

$$a_{i1} x_1 + a_{i2} x_2 + \dots + a_{in} x_n \leq b_i \tag{4}$$

then this constraint can be written in the form of an equation by adding a non-negative variable s_i to the left hand side and writing

$$a_{i1} x_1 + a_{i2} x_2 + \dots a_{in} x_n + s_i = b_i \tag{5}$$

The variable s_i is called a slack variable because it measures the slack in the original inequality. If the constraint is written as a greater-than condition then by subtracting a non-negative slack variable this can be written as an equation.

The objective function (3) is in standard form when it is to be minimized. If in fact an objective function is to be maximized

$$k_{i1} x_1 + k_{i2} x_2 + \dots + k_{in} x_n = \text{maximum} \tag{6}$$

then this can be put into standard form by writing

$$-k_{i1} x_1 - k_{i2} x_2 - \dots -k_{in} x_n = \text{minimum} \tag{7}$$

The standard form is usually a necessity for many of the solution techniques to converge.

The Assignment Model

Using the general linear programming model the assignment model can now be formulated. Assume k candidates are to be assigned to k tasks. Let x_{ij} be the fraction of time the ith man spends on the jth task and, again, let c_{ij} be the proficiency or effectiveness the ith man has for the jth task. Then

$$x_{i1} + x_{i2} + \dots + x_{ik} = 1 \qquad (8)$$

if each man is to be fully occupied. And

$$x_{1j} + x_{2j} + \dots + x_{kj} = 1 \qquad (9)$$

if each task is to be filled. The constraints can be written in more compact form as

$$\sum_{i=1}^{k} x_{ij} = 1 \quad j = 1, 2, \dots, k \qquad (10)$$

$$\sum_{j=1}^{k} x_{ij} = 1 \quad i = 1, 2, \dots, k \qquad (11)$$

The objective function would become

$$c_{11}\, x_{11} + c_{12}\, x_{12} + \dots + c_{ij}\, x_{ij} +$$

$$+ \dots + c_{kk}\, x_{kk} = \text{maximum} \qquad (12)$$

or

$$\sum_{i=1}^{k} \sum_{j=1}^{k} c_{ij}\, x_{ij} = \text{maximum} \qquad (13)$$

where the double summation indicates the values are to be summed over all indices i, j. Obviously, the x_{ij} are constrained to be non-negative since negative values would have no physical meaning.

This model has one interesting property that other linear programming models do not have. Since the right hand terms of the constraint equations are integral it can be shown that the values of the variables must also be integral. Further, since the constant terms are unity, the variables cannot exceed unity and hence, in view of the non-negative condition, the x_{ij} can take only the values zero or one. This means any optimum solution would assign one man full time to one task during any finite schedule time. To illustrate the model consider the following simple example. Suppose three men are to be assigned to three tasks. The proficiency indices of each man for each of the tasks are given in the table below.

	First Candidate	Second Candidate	Third Candidate
Task A	4	3	7
Task B	6	5	8
Task C	4	4	6

Table I
Proficiencies of Three Candidates for Three Tasks

The equations of constraint for this example would be

$$\left.\begin{aligned} x_{11} + x_{12} + x_{13} &= 1 \\ x_{21} + x_{22} + x_{23} &= 1 \\ x_{31} + x_{32} + x_{33} &= 1 \\ x_{11} + x_{21} + x_{31} &= 1 \\ x_{12} + x_{22} + x_{32} &= 1 \\ x_{13} + x_{23} + x_{33} &= 1 \end{aligned}\right\} \qquad (14)$$

And the objective function would be

$$4x_{11} + 3x_{12} + 7x_{13} + 6x_{21} + 5x_{22} + 8x_{23} +$$

$$+ 4x_{31} + 4x_{32} + 6x_{33} = \text{maximum}$$

For this example there are 3! combinations of assignments. The possibilities are shown below with the relative effectiveness of each;

Task A	c_{iA}	Task B	c_{iB}	Task C	c_{iC}	Relative Effectiveness
y_1	4	y_2	5	y_3	6	15
y_1	4	y_3	8	y_2	4	16
y_2	3	y_1	6	y_3	6	15
y_2	3	y_3	8	y_1	4	15
y_3	7	y_1	6	y_2	4	17
y_3	7	y_2	5	y_1	4	16

Table II
Possible Assignments of Three Candidates for Three Tasks

where y_1, y_2, and y_3 refer to the first, second, and third candidates respectively. Clearly, the fifth possibility would be the optimum.

It should be clear from this example that as the number of candidates and tasks increases, a listing of all possibilities to choose an optimum would not be practical.

We now have a suitable model for assigning candidates to tasks based upon each candidates proficiency for each task. For a time interval of arbitrary length the smae model would be a schedule of task assignments. The collection of models, for the total mission time, would represent an optimum schedule.

Extensions of the Basic Model

Crew Selection

Suppose it is desired to select a crew for a particular mission. Assume the tasks necessary for successful completion of the mission are well defined (as they usually will be) and that the number of crew members needed is known. Suppose further that the proficiency index (c_{ij}) of each candidate for each task is also known. Let the number of tasks to be assigned be N and the number of candidates be K where K > N. Again, x_{ij} would be the fraction of time the ith man spends at the jth task. The constraint equations and the objective function would be in the following form

$$\sum_{i=1}^{K} x_{ij} = 1 \qquad j = 1, 2, \ldots, N \qquad (15)$$

$$\sum_{j=1}^{N} x_{ij} \quad 1 \qquad i = 1, 2, \ldots, K \qquad (16)$$

$$\sum_{i=1}^{K} \sum_{j=1}^{N} c_{ij}\, x_{ij} = \text{maximum} \qquad (17)$$

The system (15) is in standard form, but the system (16) is not. Then as in equation (5), K non-negative slack variables may be added to (16) to transform it to standard form, as

$$\sum_{j=1}^{N} x_{ij} + s_i = 1 \qquad i = 1, \ldots, K \qquad (18)$$

The slack variables would correspond to the unassigned candidates and take the form of imaginary tasks. The proficiency indices related to these tasks are obviously zero since an unassigned candidate could have no effect on the optimum. The objective function would take the form

$$\sum_{i=1}^{K} \left\{ \sum_{j=1}^{N} c_{ij}\, x_{ij} + \sum_{j=N+1}^{K} c_{ij}\, s_i \right\} = \text{maximum} \qquad (19)$$

where the second term in the parentheses is identically zero. The constraint matrix for the above example would take the form

$$\begin{array}{ccccccc} x_{11} & x_{12} & x_{1N} & s_1 & 0 & 0 & 0 \\ x_{21} & x_{22} & x_{2N} & 0 & s_2 & 0 & 0 \\ x_{N1} & x_{N2} & x_{NN} & 0 & 0 & s_N & 0 \\ x_{K1} & x_{K2} & x_{KN} & 0 & 0 & 0 & s_K \end{array} \qquad (20)$$

It should be noted that only N of the x_{ij} would have values different from zero upon solution, and K-N of the s_i would have non-zero value. All of the remaining variables would be zero. The non-zero x_{ij} would represent the crew chosen.

Upper Bounds

Much has been written concerning the optimization of time cycles and work/rest ratios. It is important to establish the individual work/rest cycles for crew candidates such that crew effeciency can be maintained for the complete mission. In addition, the proportion of crew members required for relief purposes must be found. For space missions, this latter consideration will, of course, be very severly limited due to weight, thrust, and cabin size limitations.

The consideration of such work/rest cycles may be reflected in the model by constraining the variables as follows

$$0 \le x_{ij} \le M_{ij} \; (M_{ij} < 1) \text{ for some } i, j \qquad (21)$$

that is, by not allowing one man to be assigned full time to one task. The upper bound M_{ij} in expression (21) is the fraction of the task duration for which the ith man is capable of performing without any appreciable loss in effectiveness. Thus the extension of the model can be summarized as, using (10), (11), and (13)

$$\left.\begin{aligned}
&\sum_{i=1}^{k} x_{ij} = 1 \qquad j = 1, 2, \ldots, k \\
&\sum_{j=1}^{k} x_{ij} = 1 \qquad i = 1, 2, \ldots, k \\
&\sum_{i=1}^{k} \sum_{j=1}^{k} c_{ij}\, x_{ij} = \text{maximum} \\
&x_{ij} \geq 0
\end{aligned}\right\} \quad (22)$$

$$x_{ij} \leq M_{ij} \qquad \text{for some or all } i, j \qquad (23)$$

where (22) is the original system and (22) plus (23) is the extended system, which includes the upper bounds on the variables.

In general, all of the variables will be constrained for the sake of consistancy. However, in practice, some of the M_{ij} may be made so large they have no effect upon the solution.

Network Representation

In recent years PERT-PEP management information techniques have become increasingly popular. The use of these networking techniques have been excellent aids to management personnel for scheduling and identifying troublesome areas in the schedule. The use of network techniques may also be an aid in assigning crew members for space missions. The network in figure I illustrates the possible assignments of three candidates for three tasks.

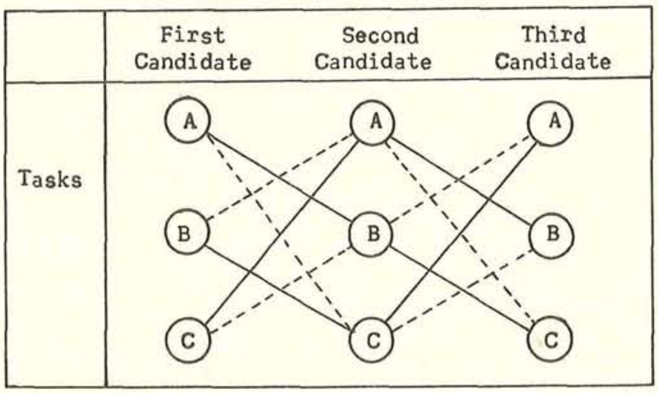


Figure I
Network Illustrating the Possible Assignment of Three Candidates for Three Tasks

The use of the solid or dotted lines is a graphic representation of the condition that all tasks be filled and all candidates be assigned. For example, if the first candidate is assigned task B, then the only decision to be made is whether path BAC or BCA is to be followed to complete the assignments. Of course, this decision is based on the relative proficiencies associated with each path. The above network is actually a combination of two networks, one overlayed on the other, each of which gives three of the possible assignments. The dotted constraints are one network, and the solid constraints are another.

The use of a network would be very limited, however, since an increase in crew candidates and/or tasks greatly increases the complexity of the network. Since a network illustrating the assignment of N candidates to N tasks has N! possible assignments, the number of constraint lines tend to confuse the network as N increases. For the network shown there are 12 constraint lines and, in general, for the assignment of N candidates to N tasks the network would have $N(N-1)^2$ constraint lines.

Bibliography

1. Ackoff, Russel L., (Editor), Progress in Operations Research, Volume I, John Wiley & Sons, New York; 1961.

2. Garvin, Walter W., Introduction to Linear Programming, McGraw-Hill Book Company, Inc., New York; 1960.

3. Mood, A. M., Introduction to the Theory of Statistics, McGraw-Hill Book Company, New York; 1950.

4. Ray, James T., Martin O. Edward, and Alluisi, Earl A., Human Performance as a Function of the Work Rest Cycle, A Review of Selected Studies, National Academy of Sciences - National Research Council, Washington D.C.; 1961.

REDUNDANT ADAPTIVE FLIGHT CONTROL SYSTEMS AS USED IN SPACE VEHICLES

By John N. Mitchell and Allyn J. Forsman
Minneapolis-Honeywell Regulator Company
Aeronautical Division
Minneapolis, Minnesota

Introduction

High reliability requirements of today's aerodynamic and space flight control systems have generated many new concepts. In recent years, the role of the automatic flight control system has changed. Originally considered an accessory item, it has reached the point where success of the intended mission depends upon its satisfactory operation. Present-day high-speed aircraft, for instance, exhibit poor stability characteristics at certain flight conditions, making it very difficult for the pilot to control the craft, much less perform his intended mission, without stability augmentation system.

In manned space vehicles the need is even greater. During the critical periods of launch and exit from, and re-entry into the earth's atmosphere, vehicle flight path and attitude will have to be maintained within very close limits, not only to maintain the desired course but also to prevent the vehicle's destruction from excessive heating rates and aerodynamic forces. The required tight control, coupled with poor vehicle stability, presents a control problem which is beyond a human pilot's capabilities.

Naturally, this growing dependence on the automatic control system has focused greatly increased attention on its reliability. While performance demands upon future systems are great, reliability requirements are the most difficult to meet. In comparison with present capabilities, it is perhaps the single area in which the greatest improvement over existing techniques must be made to satisfy projected future control system requirements.

Methods To Improve Reliability

System complexity has increased by leaps and bounds due to the high performance characteristics of new vehicles and the greater demands to perform more functions automatically. Attempts to simplify control systems have resulted in minor improvements in reliability.

Improving reliability through the development of highly reliable parts has not been adequate to meet the demands of flight control systems for space vehicles. The reliability of present flight control systems for aerodynamic controlled vehicles ranges from 100 to 500 hours mean-time-between failures.

These systems may be improved by a factor of 4 or 5 through the use of high reliability parts. Much emphasis has been given to electronic part improvement on programs such as Minuteman. In mild environmental applications these parts may exhibit improved reliability by an order of magnitude or more.

However, this improvement cannot be achieved in the more severe space environments. To meet space reliability requirements, systems must be improved by 2 or 3 orders of magnitude.

At the present state-of-the-art, the required degree of reliability improvement can be achieved through the use of redundancy.

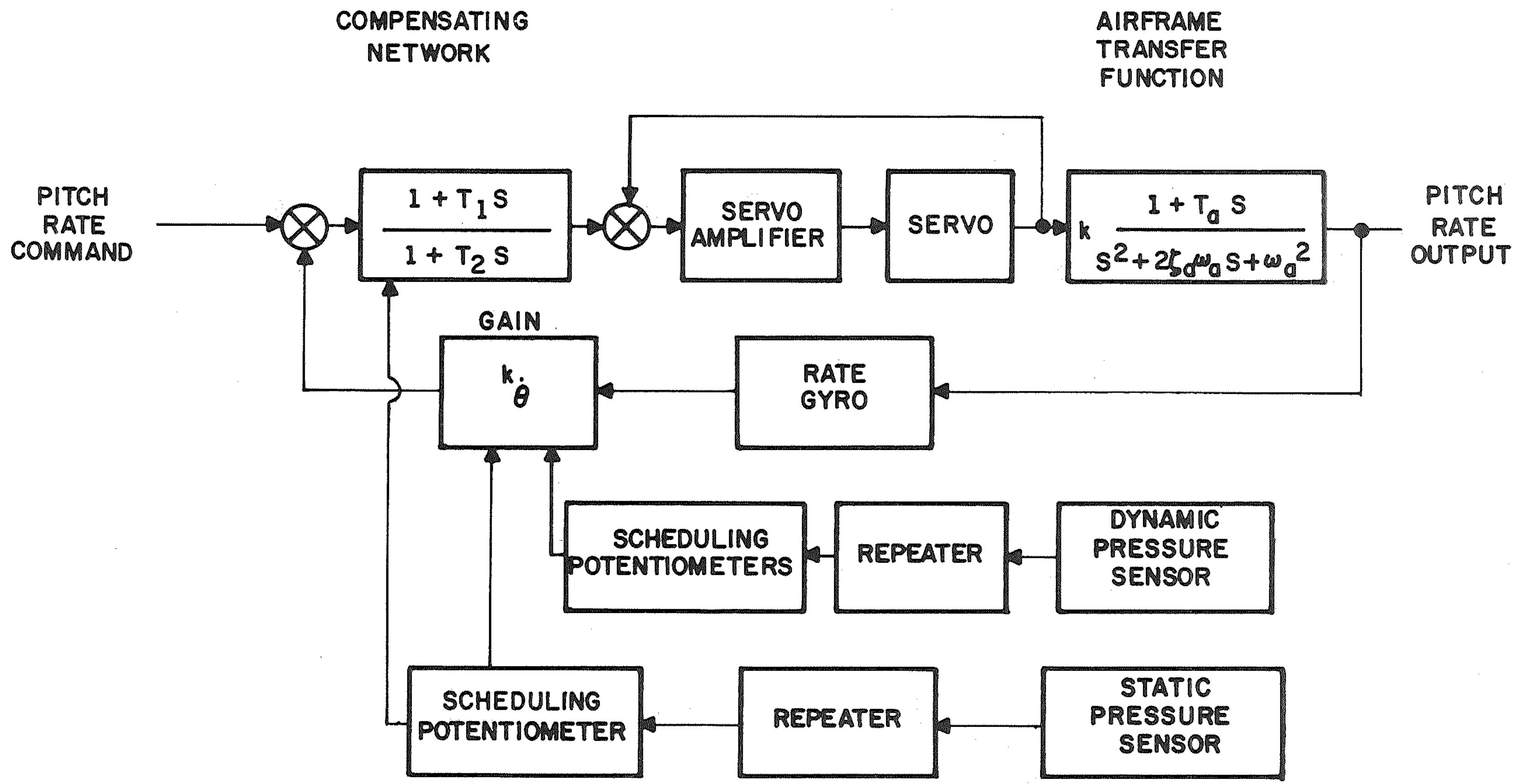
With redundancy comes the consideration of weight, volume, cost, and performance. Thus, the objective is to maximize reliability and performance while minimizing weight, volume, and cost.

To achieve this objective with a conventional control system requires a triple redundant mechanization. The operation may be the voting scheme, which results in dropping out the one channel that is in disagreement. The dual redundant adaptive control system with monitors has achieved high reliability without degradation of performance.

Adaptive Flight Control System

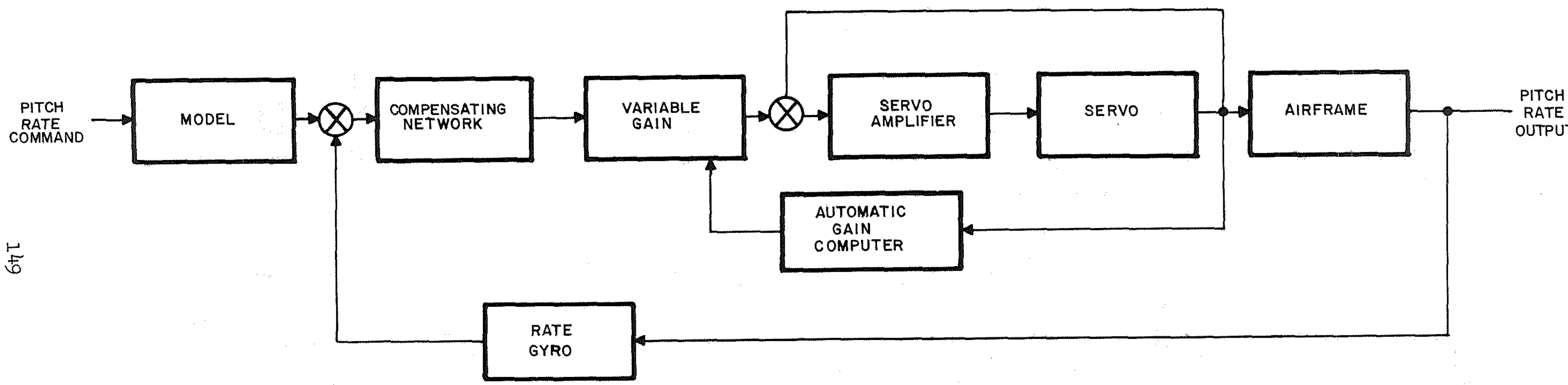
Let us compare the operation of a conventional control system and an adaptive control system.

Consider the block diagram of Figure 1, which depicts a conventional approach to the control problem. Note the airframe transfer function. The parameters ω_a^2, ζ_a, T_a, and K are, in general, functions of the airframe aerodynamic characteristics, the flight speed and altitude. These parameters might have variations as high as 50 to 1 through the flight envelope of a supersonic vehicle. Hence, to provide satisfactory damping augmentation to a vehicle with such widely varying dynamic characteristics, it is normally necessary to program the feedback gain $K_{\dot{\theta}}$, with air data information such as dynamic pressure, Mach number and altitude. In some cases it may even be necessary to program the time constants of the compensating network. The



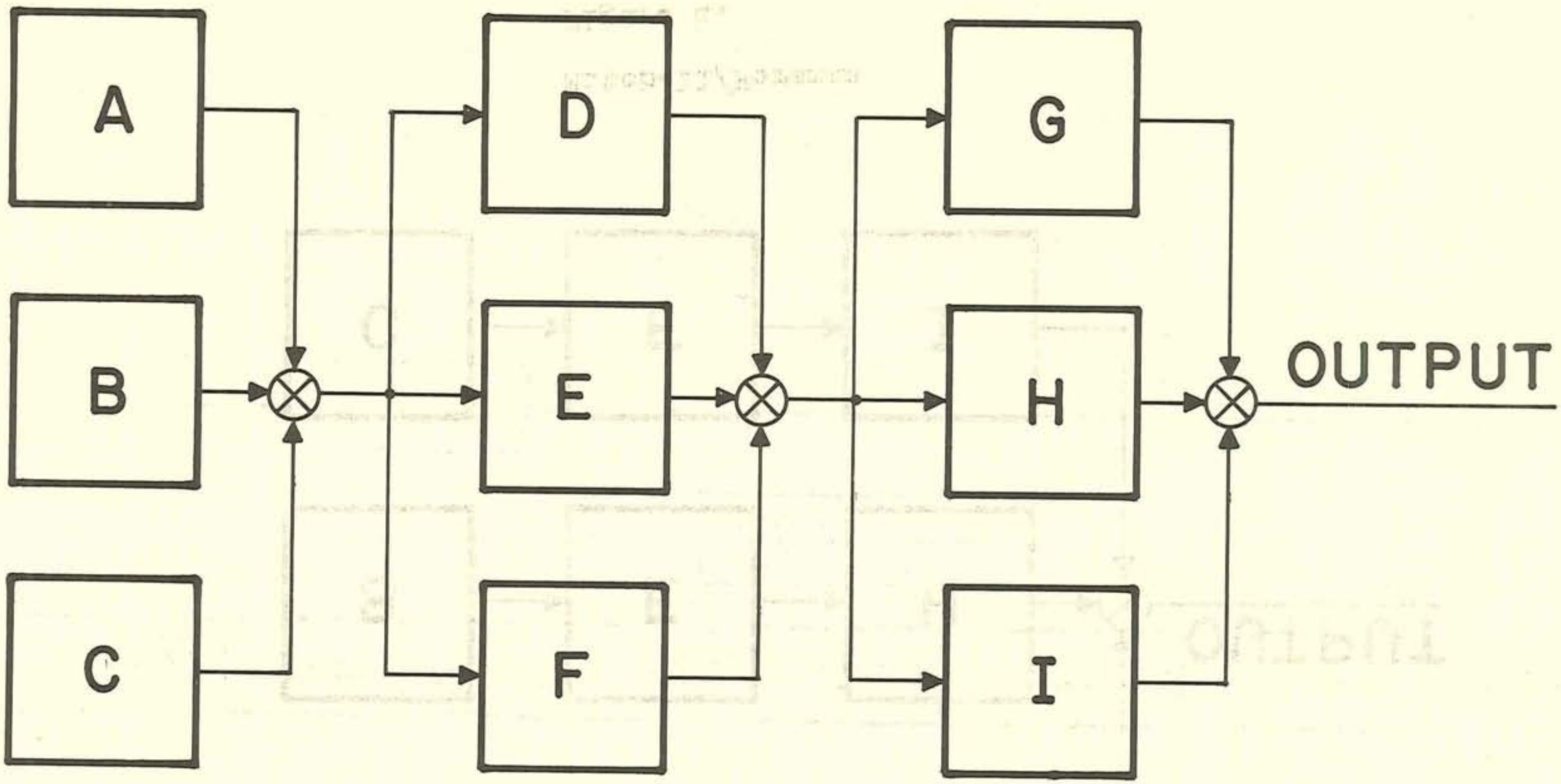
Mitchell/Forsman

Figure 1.



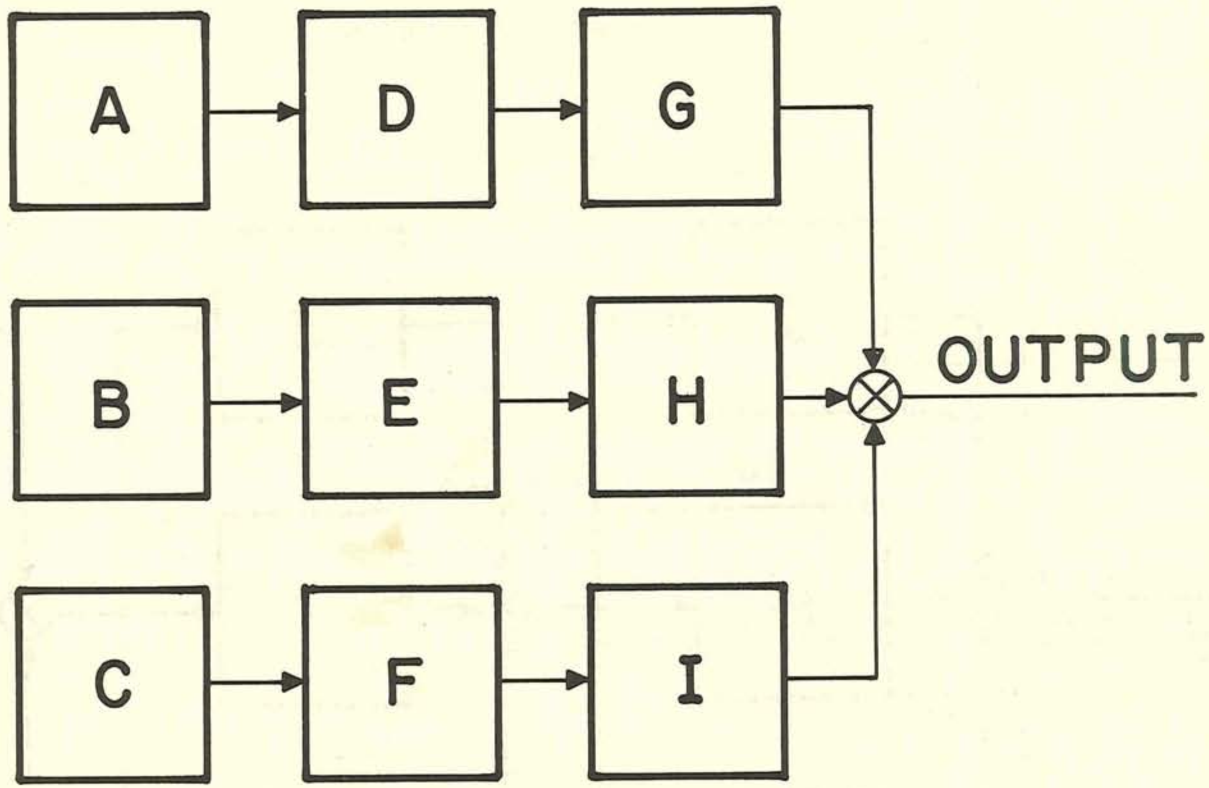
Mitchell/Forsman

Figure 2.



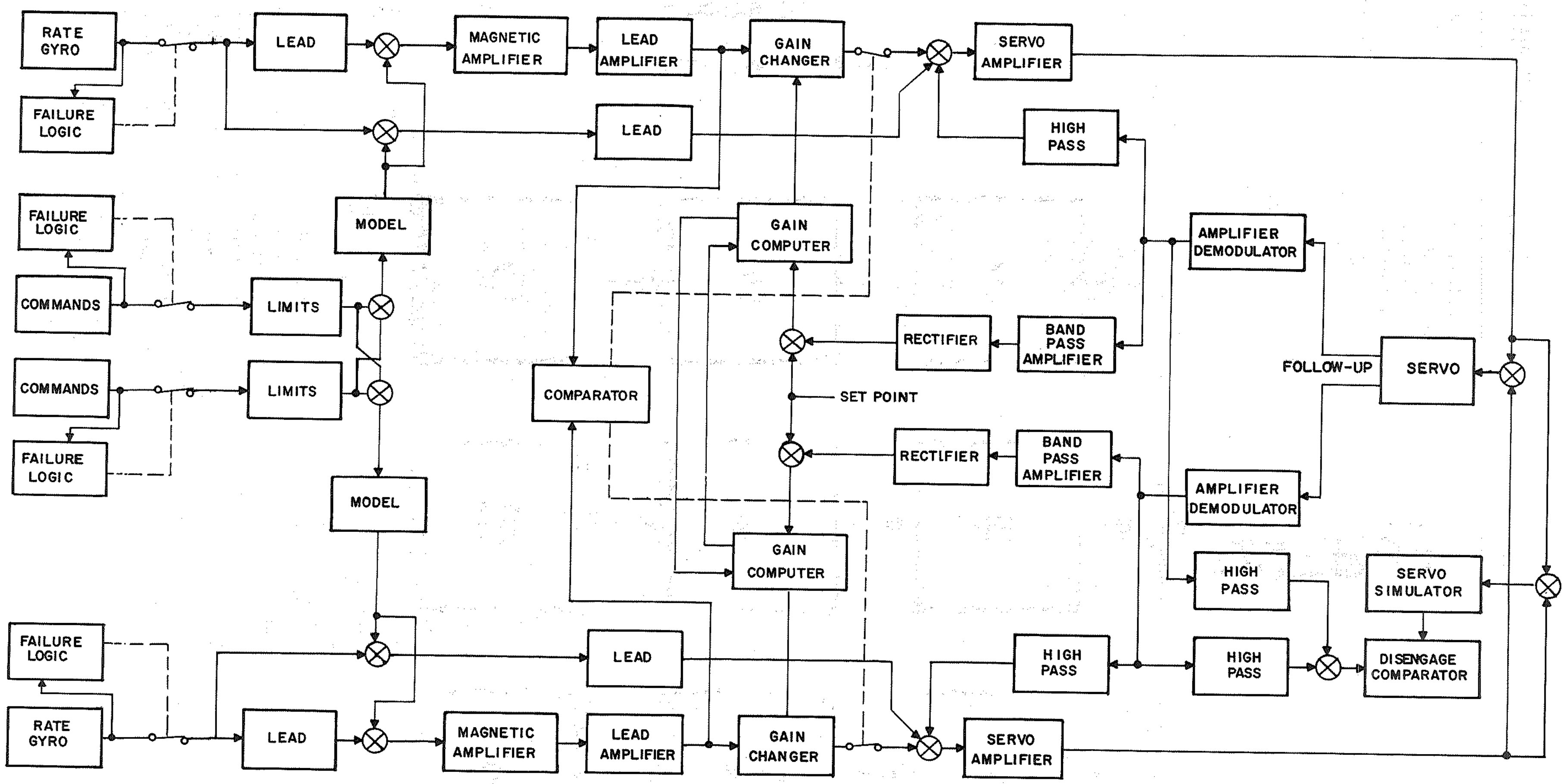
Mitchell/Forsman

Figure 3.



Mitchell/Forsman

Figure 4.



Mitchell/Forsman

Figure 5.

reliability of this simple type control system is dependent upon the reliability of the air data computer system, the motor gear-train repeaters, and the non-linearly wound potentiometers used to program the feedback parameters.

A major step in improving reliability is to eliminate the need for air data information. In 1954, Honeywell set out to eliminate gain scheduling without compromising performance. The idea was to devise a system which could effectively evaluate its own performance and alter its feedback gain to maintain a desired performance level. This was named "The Self-Adaptive Control System".

As indicated by Figure 2, a model is used to shape vehicle response to the desired response characteristics for all commands. The vehicle is made to follow the output of the model by maintaining a high-gain control loop following the model commands. The model is an electrical analog simulating the desired dynamic characteristics of the vehicle. In other words, when an electrical signal is fed to the model network, the output of the network is an electrical signal representing the desired output response of the vehicle. By comparing the vehicle response with the model response and feeding the error signal to an authoritative controller, it is possible to enforce correspondence of the vehicle response to the model response. This control loop (including a rate gyro, amplifier, variable gain, servo, surface actuator, and aircraft) must have a bandwidth at least three times the bandwidth of the model to prevent further shaping of the command due to the controller dynamics. This wide bandwidth is obtained primarily through automatic gain control, which continuously seeks the maximum gain operating condition. This gain level is called critical gain, and it is detected by means of a small-amplitude limit cycle. The amplitude of this limit cycle (for the F-101 system this amounted to 0.1 degree of surface deflection) is compared to a reference amplitude set point and tightly controlled to this reference amplitude by the gain computer. Any tendency for the limit cycle to become larger results in an immediate gain reduction, while loss of the limit cycle initiates an immediate gain increase.

This adaptive technique therefore provides uniform aircraft response to commands throughout the flight envelope by varying the flight control system gain as an inverse function of the aircraft surface effectiveness through the operation of the self-contained gain computer. Thus, the adaptive concept is independent of air data inputs from a central air data computer.

The adaptive system differs from the conventional system in that a model and an automatic gain computer have been added and the air data scheduling have been deleted. The Honeywell self-adaptive concept was first successfully demonstrated in an F-101 supersonic aircraft.

Adaptive System Reliability

The self-adaptive system previously described is capable of adjusting its operation, through the gain changer, to compensate for component deterioration. Obviously the gain computer, sensing the performance of the entire aircraft-control system loop, cannot detect whether changes in this performance are caused by changes in aircraft characteristics or changes in component performance. Hence, it compensates accordingly for variations in gain or dynamic response occurring anywhere in the loop. This feature makes the system extremely tolerant of component variations and in a sense tends to upgrade component reliabilities. In a conventional system, for example, a 50 per cent decrease in gain of a particular amplifier might result in unsatisfactory operation of the system and would be considered a failure of the amplifier. In the adaptive system such a loss would be compensated for by the gain computer.

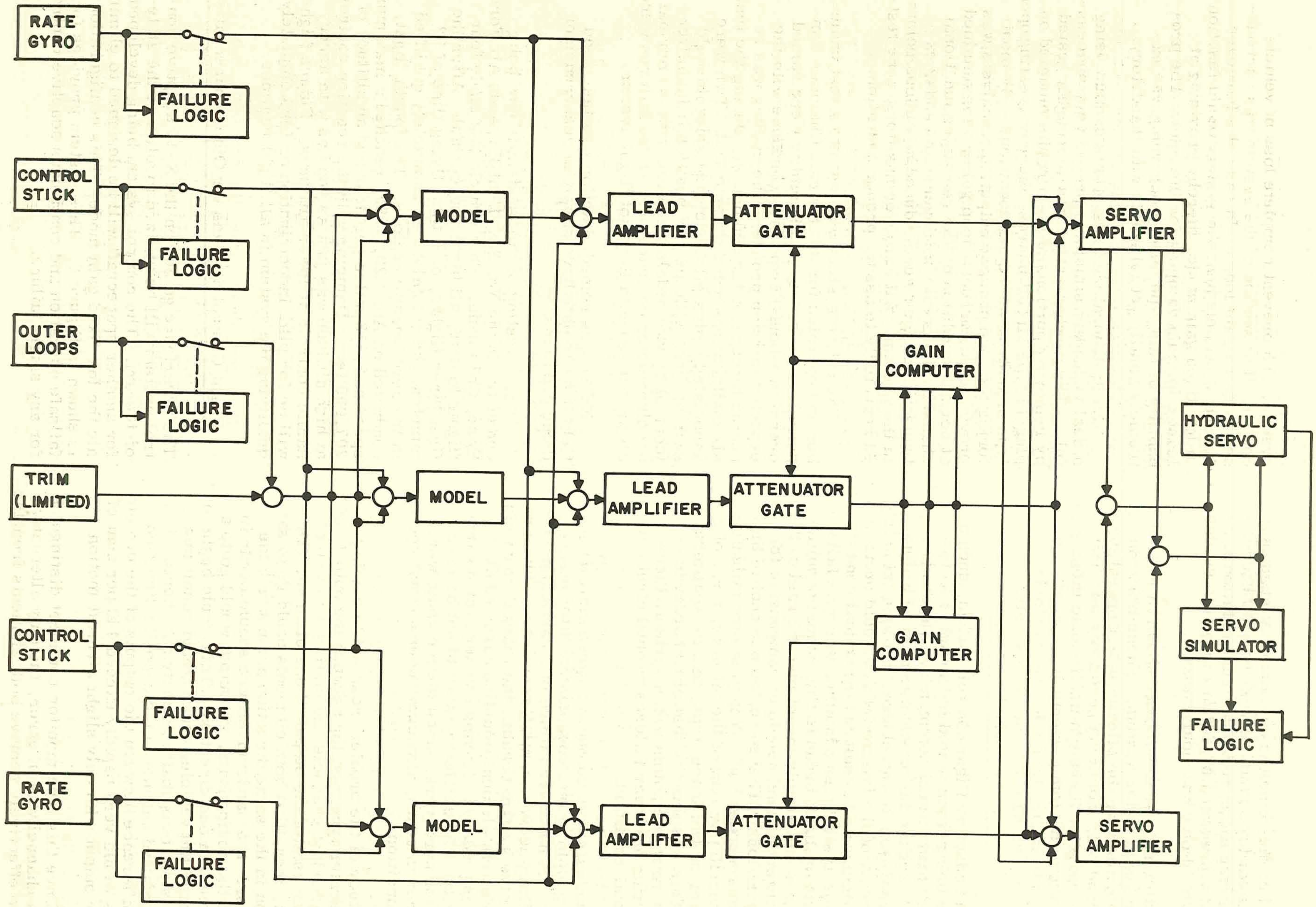
Approach to the Adaptive Control System For the X-15 Vehicle

At the outset of this program, the single adaptive control system was evaluated for use in the X-15 vehicle. The reliability analysis indicated a reliability factor of 0.995 for a one hour mission.

This system proved to be unsatisfactory for two reasons. First, the single system configuration offered no failsafety. One of the prime requirements of automatic flight control systems for hypersonic or space vehicles is that they be failsafe. This requires that the flight control system be designed such that no failure can cause vehicle destruction. Second, even though the reliability factor was reasonable for the specified mission, the system to be developed required high reliability for an extended mission period.

To accomplish both of these requirements, triple redundant systems were studied. Figure 3 is a simplified reliability mode showing the triple redundant component summing mechanization. Several complications which arose in isolating the components led to the redundant channel summing mechanization shown in Figure 4.

However, due to other limiting factors in the system, principally the reliability of the servos, it was decided to provide a dual redundant system with "automatic decision devices". This configuration provided for failsafety and continuous operation for any failure. The block diagram of this system is shown in Figure 5. The block diagram shows a single axis augmentation configuration with pilot commands. All elements are redundant, except for the servo. The predicted mean time between failures,



Mitchell/Forsman

Figure 6.

(MTBF) of the complete nonredundant augmentation system (excluding servos) was 340 hours. The corresponding redundant augmentation system had a predicted MTBF in excess of 100,000 hours based on a one-hour mission.

Additional electronics not shown in Figure 5 were included in the system. These electronics were provided for the pilot to select operational modes and hold modes. Redundancy was not used in the pilot flight system because these elements were not flight essential.

Dual Redundant System

The adaptive flight control system, such as the one being flight tested in the No. 3 X-15 vehicle, lends itself exceptionally well to redundant mechanization and provides failsafety. After analysis, it was evident that approximately 90 per cent of the failures which would occur in the system would result in a no-signal condition. Since the system was adaptive, this type failure posed no problem because a no-signal condition in one channel simply meant that the gain of the other channel would double to compensate for the signal loss. Therefore, 90 per cent of the problems were solved. Yet to ensure failsafety the other 10 per cent of the failures, i. e., of a hardover or full output type, had to be eliminated. This was done by installing hardover monitors at strategic points in the system, thereby converting hardover failures to open circuit or no-signal condition.

Analysis pointed out a major deficiency in provisions for continuous control after a single failure. A hardover failure of a particular element (lead network amplifier) would result in an ineffective system because the channel containing the defective element would be balanced by the surviving channel, leaving no range for control authority. These elements could not be monitored for hardovers, since their outputs were required to reach maximum under normal operating conditions.

Study of the problem resulted in placing a comparater type monitor between the outputs of the redundant channels and setting it to trip at 140 per cent of the output of one element. This meant, then, that both elements could go to saturation in the same direction and not trip the monitor. If a hardover failure should occur in one of the components, its output would go to a maximum in one direction. This would begin to command the vehicle, which would result in a gyro output of opposite polarity and thereby drive the nonfailed channel in the opposite direction. The difference between the outputs of the two elements would very rapidly exceed 140 per cent of either output with only slight aircraft motion.

Since this type monitor could not distinguish which channel was in error, the only alternative was to effectively remove both elements from the system. To prevent complete loss of vehicle control, this section of the system was surrounded by fixed gain loops. In case of a hardover failure of this element the system would function in low fixed gain mode, thereby providing at least minimum damping for the pilot. The probability of this type failure occurring was extremely small, yet failsafety was mandatory.

Early laboratory tests of this system using a dual redundant simulator proved very successful. The mechanization was thoroughly tested by removing portions of the circuits mounted on plug-in type circuit boards, thereby creating open type signals or no-signal conditions. By monitoring the gain changer output, the analysis was proven to be correct: loop gain was maintained at normal condition by the remaining functional channel. To create hardover commands, extraneous voltages were induced at various points in the system. All hardover monitors were tested repeatedly to assure proper operation.

The entire system was put into a test chamber and operated for 300 hours. Chamber temperature, pressure, and humidity were varied over a two-hour period in accordance with the expected mission profile. The cycling was repeated throughout the 300 hours. During the test six malfunctions were experienced. Two were associated with a pilot operated solenoid-held switch; three with the yaw position transmitter (control by yaw pedals); and one with the normal accelerometer comparator. These failures were all associated with the pilot flight system.

Necessary remedial action was taken and field tests to date have shown no recurrence of these problems.

Flight testing of this system is now being conducted in the No. 3 X-15 at Edwards Air Force Base, California. This vehicle has made four flights to date, all highly successful. After the first three flights, or a total flying time of 32 minutes, the autopilot was completely qualified in the aerodynamic regions. The fourth flight, conducted on April 20, 1962, reached a maximum speed of 3,818 miles per hour and an altitude of 207,000 feet. Damping with the reaction controls at high altitude was just as good as with aerodynamic controls at lower altitudes. Future flights will be for pilot indoctrination or for completely qualifying the system in all flight regimes.

Flight Control Systems for Other Spacecrafts

The experience gained on the X-15 adaptive control system will be utilized to advance the state-of-the-art. The control system being developed for another spacecraft will be designed to eliminate the low fixed gain mode. This configuration is shown in Figure 6. This system provides for failsafe operation and continuous adaptive control for any single failure.

Space vehicles having a mission period well in excess of 100 hours will utilize all methods of achieving high reliability, such as simplification, derating, redundancy, etc. One of the principal means of achieving high reliability will be in-flight maintenance. Studies made on the redundant channel adaptive simulator have proven the feasibility of this concept. As mentioned earlier, entire circuits were removed without degradation of vehicle control. Accepting this approach, ultra-reliability of the adaptive control system can be achieved by short periods between inspection and providing a reasonable quantity of spare circuits.

Acknowledgments

Development of the X-15 adaptive autopilot was sponsored by the Flight Control Laboratory, Aeronautical Systems Division (ASD) of USAF, under Contract No. AF33(616)6610, with Lt. Robert Johannes as project officer.

SNAP RELIABILITY PROGRAM*

W. R. Vaughn
Reliability Advisor
Compact Systems Division
Atomics International
A Division of North American Aviation, Inc.
Post Office Box 309
Canoga Park, California

C. J. Brous
Director
Product Engineering and Manufacturing Department
Compact Systems Division
Atomics International
A Division of North American Aviation, Inc.
Post Office Box 309
Canoga Park, California

17280

Summary

The reliability of nuclear power systems for space applications is one of the important factors that will make this energy source practical. The study of environmental effects on the reliability of these space systems and their electronic payloads involves not only the usual conditions of space but adds to it the requirements for long term endurance and radiation resistance. The study of these effects can be expensive and time consuming. A simplified analytical technique has been developed at Atomics International which uses available test and performance data and requires limited additional testing. This program should provide reliable systems for nuclear auxiliary power (SNAP) that will be suitable for the space payload and electrical propulsion requirements of the larger systems of the late 60's and 70's.

Introduction

The application of nuclear technology to the problem of providing long lived energy sources for space utilization is a natural outgrowth of this reactor technology. This application has reached practicality now as represented by the SNAP 3 isotopic power package and is soon to be tested in the AEC program for the SNAP 10A (Figure 1), SNAP 2 and SNAP 8 nuclear reactor power packages.

The electrical energy requirement for space payloads and propulsion will soon far outstrip all energy devices except for the nuclear reactor type. In Figure 2 we see the growth of payload and electrical propulsion requirements as the booster power capabilities are increased. This is further related to SNAP 10A, 2, and 8 uses in Figure 3. You will note how these nuclear auxiliary power packages are well suited for the forthcoming systems made practical by the larger boosters.[3] The space power requirements are expected to reach the megawatt range by the 70's.

Endurance time requirements during this period will increase from one to five years of unattended operation.

These requirements for nuclear power in space must be satisfied by highly reliable systems, engineered to withstand the many environments encountered. The additional effect of nuclear power on systems and electronic payloads utilizing this power must be quantitatively determined and used in the selection of long life components. Also, the associated environments of long term endurance, hard vacuum, high temperature, micrometeorite flux, electron and proton bombardment must be integrated with this reactor environment.

More experimental effort is needed in studying the effect of the combination of radiation and extreme (high and low) temperatures and ultra-high vacuum, and further studies are required to determine the effects of high energy particles found in space on materials. Basic research to determine the mechanism of radiation effects is also needed in order to develop suitable methods for predicting life of materials and components in a radiation field.

The work at Atomics International is directed toward testing and data accumulation under these combined environments. The program will use the limited data available on radiation and space effect from many outside sources and from this testing at Atomics International. These data are being related to the reliability performance of the system by simplified analytical techniques.

* Work being conducted under AEC Contract AT(11-1)-GEN-8.

The Reliability Problem

The fundamental problem facing the reliability analyst is one of obtaining good data on the effect of radiation, heat and vacuum on electronic components and electrical materials and relating them to the reliable life of the system. While a great number of special tests have been performed, in almost every case the data taken do not provide statistical information on these environmental factors. Statistical data are lacking in terms of insufficient sample size, unsystematic variation of components (rating, manufacturing, similarity, and type), and success/failure criteria. Gross effects, of course, are known; and if assumptions are made about unincluded factor effects, quantitative values can be described.

The need to prepare reliability analyses on equipment exposed to these new combined environments requires consideration of new techniques and a re-examination of present methods. The exponential failure law ($R = e^{-\lambda t}$) is dependent upon, first, the requirement that all parts in electronic systems introduce independent sources of rapid catastrophic failures; second, the mean time between failure is dependent upon replacement of failed parts with new parts as soon as failure occurs; and, finally, the failures are random in time and, in general, representative of the sustained failure rate for the system.

Most of these conditions are not met and, even if they were, the use of this formula as the exclusive measure of survival probability is highly unconservative since only a fraction of the total failure potential is considered. The remainder of the failures are those resulting from the degrading influences of nuclear and temperature environment. Both of these categories of failure must be integrated in some manner so that a probabilistic estimate can be made of the life and performance of an electronic component exposed to this space-radiation-temperature environment.

Reliability analysis of equipment exposed to radiation, high temperature, and vacuum is dependent upon data properly taken under these environments. The data-producing test must be designed so that factor effects can be isolated or can be combined with other factors, and the combined effect determined. Sufficient levels of each factor should be selected in order that more general use of the data can be made without recourse to extrapolation. Many industrial contractors have or will have specific test requirements; and if these requirements were adjusted in terms of sample size, environmental levels, or inclusion of an additional environmental factor, it would be possible to satisfy over-all data requirements.

The Battelle Memorial Institute at Columbus, Ohio,[1] has compiled and edited the test results on electronic components and systems that have been exposed to nuclear radiation. These tests were conducted by a multitude of contractors who performed them to satisfy special technical requirements. These results have been published in a series of reports[1] and, since they describe the majority of test effort in terms of radiation environment today, they form the basic data for initial reliability analyses. It is, therefore, of interest to examine these data to determine their suitability for reliability purposes.

An examination of the contents reveals that engineering data predominate rather than statistical or reliability data. This means that failure rates are not available for insertion into a reliability formula. Furthermore, sample sizes are insufficient in most cases to establish confidence in the values of the parameters measured.

The problem, therefore, is to find a means of making maximum use of the available data in the reliability analysis. The reliability approach presented herein makes maximum use of published data and results from limited testing.

The Reliability Approach

Figure 4 illustrates generally an approach for including the radiation environment into the reliability prediction analysis.
Gross effects in terms of percent change in parameters due to radiation dose have been determined for certain types of components (Figure 4a). These values are inserted into each circuit formulae and the change in circuit output calculated (Figure 4b). This value is then compared with the circuit failure/success criteria for a determination of category. Repetitive selection of sets of component values from an assumed rectangular distribution of values is made, and in each case the circuit output calculated. This output is then compared with the circuit failure/success criteria. At least 1000 such sets are computed. The result is a ratio of success to total trials for each circuit for a specified operating time (t). The system radiation reliability is then determined by a series multiplication of the individual circuit reliabilities. In turn, the standard reliability analysis values are then multiplied by the radiation reliability for a combined system reliability (Figure 4). A general example of the above is worked out in detail in Appendix A.

Combined Environmental Testing

SNAP testing is now under way leading to information on the radiation effects for use in the reliability approach described. Reactor control systems and associated devices located in the payload dosage plane and adjacent to the reactor are being tested in combined environments, which should produce data useful in

reliability analyses.

Table I tabulates the results of preliminary tests conducted on high temperature components developed during the HOTELEC[2] program. These tests were conducted to examine the temperature extremes characteristics.

Tests on components operating normally at the conclusion of 1800 hours were continued for an additional 2184 hours for a total of 3984 hours. Results indicated normal operation. Since these tests were to establish preliminary capability, no radiation flux was included.

Further testing, which includes the radiation environment, is divided into two major divisions of environment: (1) low flux - low temperature; and (2) high flux - high temperature. (See Table II.)

The first environment represents the conditions existing in the shadow of the radiation and heat shield; and the second represents the environment on or immediately adjacent to the reactor.

Low flux - low temperature. Transistors, resistors, diodes, capacitors, and magnetic cores have been chosen jointly with the controller supplier and will be tested in-pile at expected operating temperatures and 10^{-6} Torr vacuum to determine parameter drift as a function of integrated neutron dose and gamma dose. An analysis will then be conducted, utilizing the drift rates obtained, and circuit designs will be modified as necessary as a result of this analysis.

Breadboard equipment, containing a number of typical operating logic modules utilizing parts similar to the ones that have been previously irradiated and the associated wiring, mounting hardware, and encapsulate, are also being irradiated to isolate circuit problems.

High flux - high temperature. Tests are in progress on encapsulating materials, electrical cabling, magnet wires, actuators, position indicators, temperature switch and temperature sensors.

In each case insulation resistance to ground will be checked versus core rate with temperature of 900°F to 1000°F.

Determination of electrical insulating resistors and physical strength are being checked in the case of the encapsulating materials.

Components to be irradiated are as follows:

1. Electronics parts.

   a. Transistors. 200 transistors will be mounted on one or more cards.

   b. Diodes. 30 diodes will be mounted on one or more cards.

   c. Resistors. 20 resistors will be mounted on a card or rack.

   d. 20 capacitors will be mounted on a rack (possibly on rack with diodes and resistors).

   e. Magnetic core. 5 encapsulated magnetic cores will be mounted on a card.

2. Module breadboards

   a. Transistorized modules. 18 circuit boards, each containing 5 typical modules.

   b. Magnetic core modules. 6 circuit boards identical to the above but using magnetic core logic, will be mounted with the transistorized boards.

Design for Reliability

The results of testing and analysis in many cases indicate that alternative means must be taken to provide for the long-life reliability of the components and sub-systems. The alternatives available are in terms of providing heat barriers, radiation shielding, and utilization of devices that are tolerant of heat and radiation.

The use of shielding in all terrestrial reactor installations to protect personnel is well known. The dose levels achieved in these installations are not only satisfactory for personnel but also for electronic devices. However, the weight of this shielding is great and can not be used for protection of space equipment to the same dose level. A compromise system of shielding, called a shadow shield, is used on the SNAP reactor units and limits the radiation dose at the electronic payload plane to a conservative value in terms of present equipment radiation tolerance levels. For the present, this shielding weight is satisfactory but, with increased power, the influence of this shielding in terms of increased satellite weight with increased reactor power will become progressively critical. Figure 5 illustrates this situation. Maintaining a fixed radiation dose at the equipment plane with approximately the same shadow shield concept, the weight of the shielding will increase exponentially with logarithmic increase in reactor thermal power.

Radiation tolerant devices. Various devices which, by virtue of their construction and material selection are tolerant of heat and radiation, are under study for reactor applications at Atomics International. Some of these devices are ceramic vacuum tubes,

wire-wound resistors, and thermionic modular electronic units. The mounting and integration of these units for useful application is also being pursued. Much work needs to be done in this area, and a strong recommendation is tendered to electronics systems engineers to seriously concern themselves with circuits utilizing these devices for basic actuation, sensors and control systems.

Drift tolerant circuits. The net effect of nuclear radiation on electronic components is predominantly that of parameter drift with dose rate. The tolerance of a circuit to that characteristic is of fundamental importance since many circuits are dependent upon precise values for each component. Certain circuits, however, can be chosen which would allow a broad band of component values and still operate successfully. Nevertheless, a sufficiently broad application of this approach is highly unlikely.

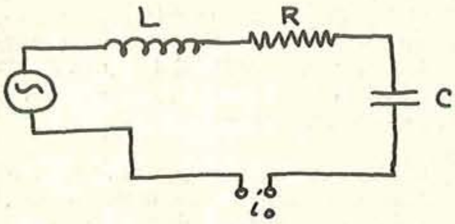
In the three alternatives described, the underlying requirement in each is the exact knowledge of the nature of the radiation effect. This is true not only for the designer but also for the reliability analyst.

Conclusion

Prediction of the life capability and functioning characteristics during the component life, as well as failure probability, lies within the technical framework of the reliability analyst; and it is in this area that the usefulness of the statistical method can be demonstrated. Binominally or exponentially based demonstration plans for long lived reactor power equipment are simply not reasonable in terms of time and money. Therefore, new techniques are required both in analysis and in demonstration. The analysis and testing procedures in use at Atomics International represent one approach. Others are undoubtedly available. In any event, it is believed that the solution will constitute a joining of engineering design analyses and statistical hypothesis.

Appendix A
Detail Method for the Reliability Approach

An approach to reliability analysis has been selected by Atomics International which makes use of presently available data and data from limited tests. To illustrate this approach, a simple circuit with resistive, inductive, and capacitive loads is used; and the time dependent effect of radiation on the circuit current flow will be calculated.



Wiring Diagram

Description: The function of this circuit is to modify the input voltage by means of electronic components contained in the circuit. This modification results in a certain output current i_o. When i_o is greater than a certain value A, this function is satisfactorily performed. However, when i_o is less than a certain value B, the function is not performed and a failure has occurred.

COMPONENT DESCRIPTION	RATING				STRESS OPER/RATED	TOTAL FAILURE RATE
	%	VOLTS	WATT	OTHER		%/1000 HR
1. CARBON COMPOSITION RESISTOR -R	1	-	1/2-1	1 MEGOHM	.8	.02
2. R. F. CHOKE -L	-	225	1-2	2H	.4	.007
3. ELECTROLYTIC CAPACITOR -C	-	200	-	$4 \mu\mu F$	.2	.01

The purpose now is to examine this circuit in a way that a prediction can be made in terms of the probability of operation after time "t". There are two effects which must be examined: (1) sudden failures due to electrical, mechanical and thermal stress, and (2) degradation failures due to the same stresses but in combination with radiation. The main difference in the two effects is due to the radiation dose which, by virtue of the accumulative effect, is time dependent.

Circuit values are selected nominally to the operating rating established in accordance with design reliability goals. This circuit, therefore, has a probability of successful operation equal to $R = \sum_{n=i}^{n=n} e_i^{-\lambda it}$. The circuit is now exposed to a nuclear flux of ($10^9 n/cm^2/sec$). After 10^3 seconds, the circuit has accumulated approximately $10^{12} nv_0 t$ neutrons of a broad energy band. The effect on each component can be estimated from the data contained in R.E.I.C. reports[1], in terms of percent change in parameter vs. radiation dose (sometimes temperature effect is included). See Figure 6 for example. Limiting boundaries are noted between the curves at a certain radiation dose for each sample.

COMPONENT	BOUNDARY VALUES	(Δ PARAMETER)					% CHANGE	
TIME IN SECONDS	t_1 = 10,000		t_2 = 100,000		t_3 = 1,000,000		t_4 = 1,800,000	
1. RESISTOR (1 MEGOHM)	-1	-3.8	-2.5	-5.0	-5.0	-7.0	-4	-6
2. R. F. CHOKE (2H)	-15	-50	-15	-65	-15	-50	-10	-40
3. CAPACITOR ($4 \mu\mu f$)	-5	-20	-5	-30	-5	-10	-10	-40

In each case, (t_1, t_2, t_3, t_4) the boundary values are changing. The time factor is introduced because of the life prediction requirement; and since the effect of neutrons is accumulative, the flux rate data in Figure 6 can be multiplied by time in seconds and the total damage at time (t) determined.

Since many considerations are intermeshed in these results, the boundaries are considered range values for a stochastic variable; and, without assuming a normal distribution, values are selected between these boundaries using a rectangular random table. Each circuit component is evaluated in this manner and at time "t_1" a set of component values is obtained and inserted into the circuit analysis. The circuit values are computed, and output value obtained. This output value is then compared with circuit success or failure based upon previously established criteria. At least 1000 repetitions of these selections are made. In each case the calculated output is compared with this success/failure criteria. The frequency distribution of these total values is then examined and a probability of success statement made for time "t_1". The effect of integrated flux dosages for additional times (t_1, t_2, t_3, t_4, . . . t_n) is also determined, and probability estimates for these time intervals established. (See Table III.)

In order to handle the random catastrophic failure prediction, it is necessary to examine the circuit stress variation in terms of change in operating to rated stresses with accumulative flux dosage (Table IV). For example, circuit current is governed by the resistivity load; therefore, changes to the resistive elements due to radiation at each time interval can be noted as an increase or a decrease in operating circuit current stress. Failure rate values can, therefore, be adjusted, using presently available curves for an estimate of the random catastrophic failure probability. Both probability calculations can be programmed on a digital computer and the results multiplied for an estimate of the probability of success. For each time interval, the adjusted random failure rate is obtained by noting the average value for the circuit current (average over 1000 trials) and using this value as the numerator in the operating/rated ratio in failure rate curves.

In estimating the total probability of success (R) of the circuit, the probability of functioning success (Table III) for each time (t) is considered independently of the random catastrophic failure events; however, system survival is dependent at any time "t" on the success of each event; therefore, R_f is multiplied by R_r.

The usefulness of an approach of this type is dependent upon substantial data gathered in a systematic manner whereby individual factors can be isolated and the interactions determined. This problem, however, is very complex since so many factors are involved. The complexity can be visualized by considering the factorial design of Table V for determining the significant factor effects for a single class of resistors. Table VI illustrates the additional possible combinations of resistors and other components which make this type of solution so complex. On the other hand, small changes in testing techniques can provide substantial increases in data that would be useful for reliability analyses. For example, consider Figure 7 as reproduced from R. E. I. C. Report No. 10.[1] This figure describes the flux for diodes, Part No. 4JA60B (G.E.) at two temperatures. The curves are in sets and represent boundary values for the four diodes checked at 25°C and the two at 150°C. The usefulness could have been enhanced markedly by increasing the sample size at each temperature to at least 30 and by adding one additional temperature point. In so doing, it would be possible to handle the data in such a manner that the degree of certainty in the values obtained in the tests could be established. The additional test point also allows accurate cross plotting because of the increased sample size. Therefore, in each test contemplated, adequate sample size and number of points should be included so that a broader application of the results can be accomplished.

References

1. Radiation Effects Information Center, Battelle Memorial Institute, Columbus, Ohio.

   a. Report No. 10, "The Effect of Nuclear Radiation on Semiconductor Devices", April 30, 1960.

   b. Report No. 12, "The Effect of Nuclear Radiation on Electronic Components", April 30, 1960.

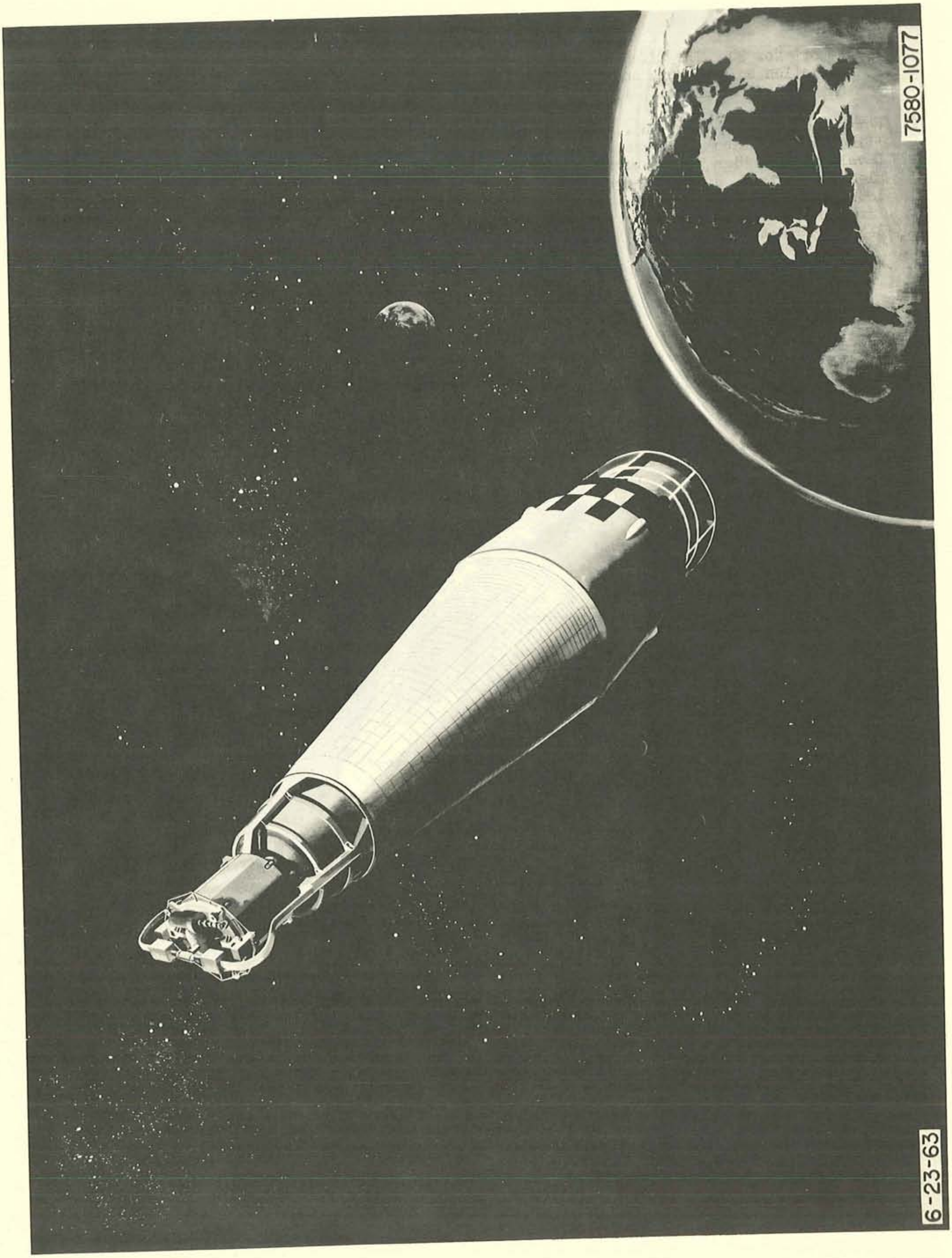
   c. Report No. 15, "The Effect of Nuclear Radiation on Components", February 15, 1961.

   d. Report No. 18, "The Effect of Nuclear Radiation on Electronic Components, June 1, 1961.

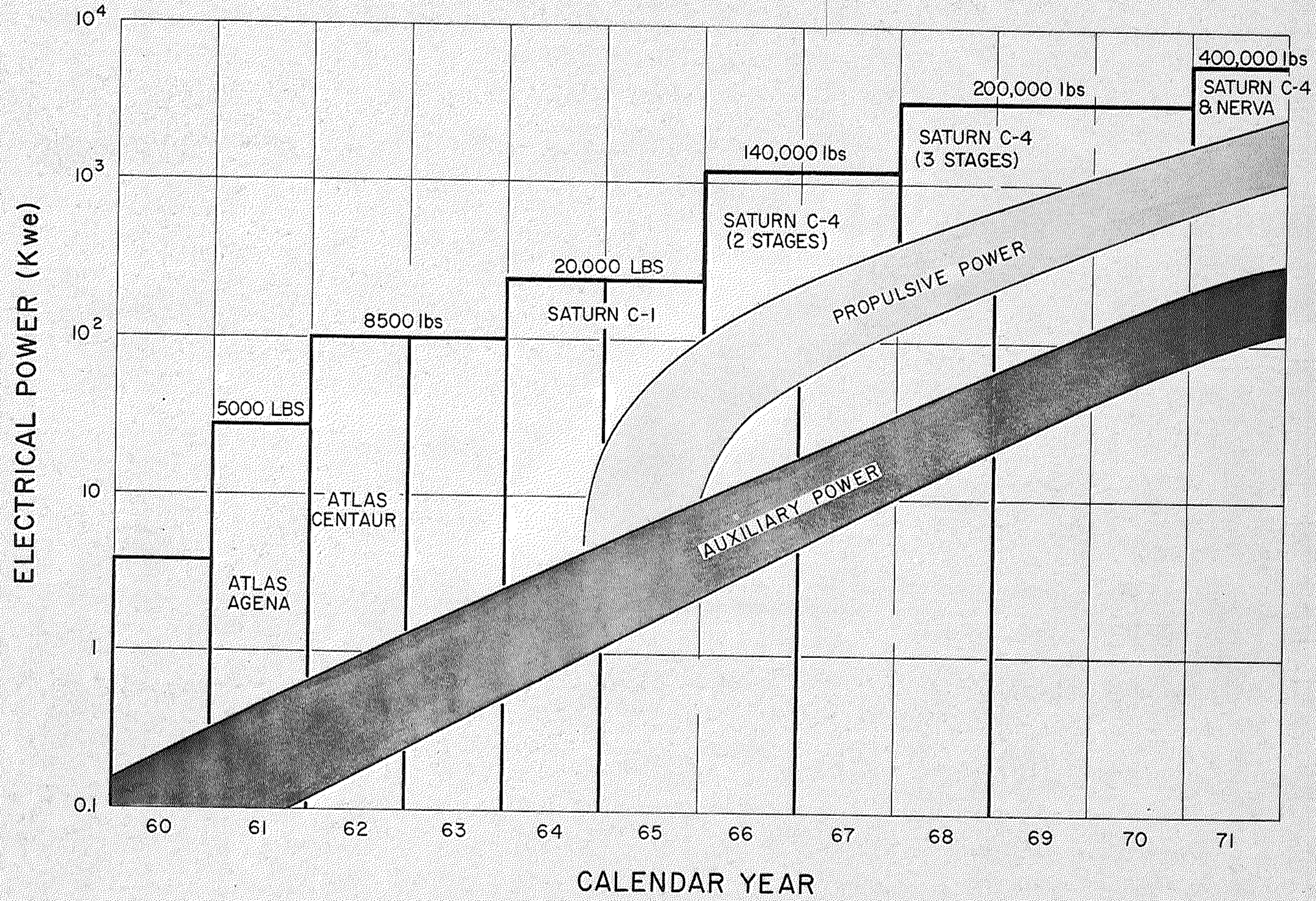
e. Report No. 20, "The Effect of Nuclear Radiation on Resistors and Resistive Materials", January 15, 1960.

2. North American Aviation, Inc., NA-57-959, "Bimonthly Technical Progress Report for Development of High Temperature Aircraft Electric System", covering period September, 1959, to May, 1961. Reports 14 through 23. Performed under Air Force Contract AF-33(600) 35489, Project No. 7-(15-6058)-60197.

3. "Aircraft & Missiles", May 1961.


7580-1077
6-23-63

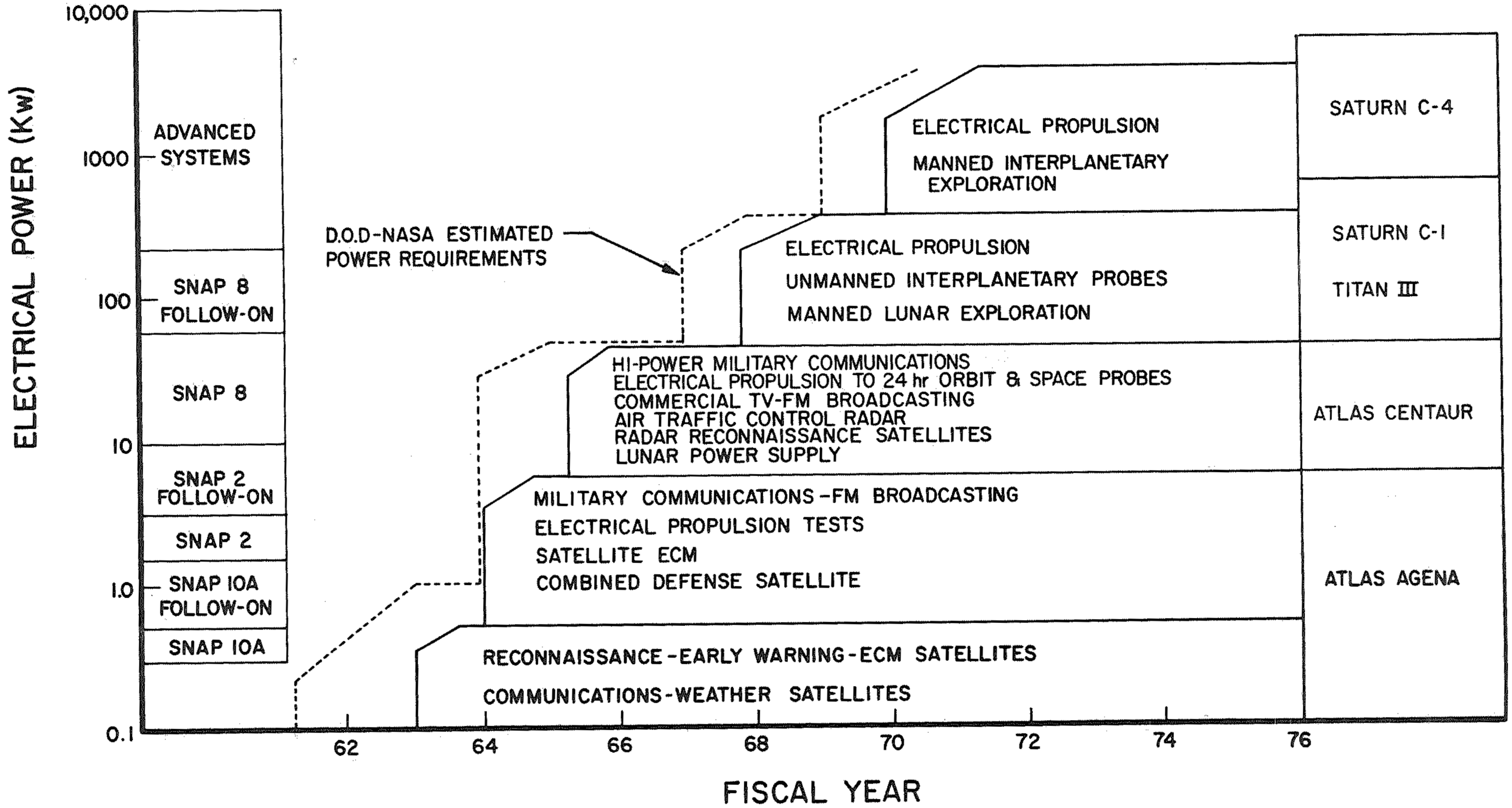
SPACE POWER REQUIREMENTS



12-29-60

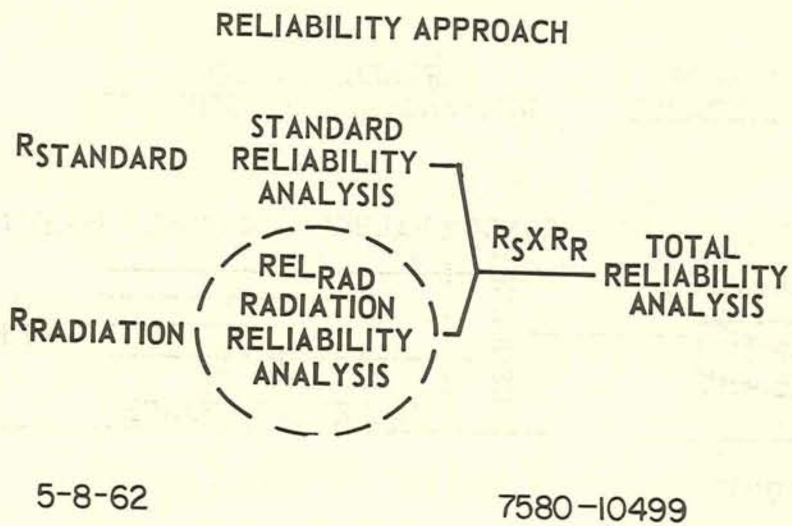
7590-A0115

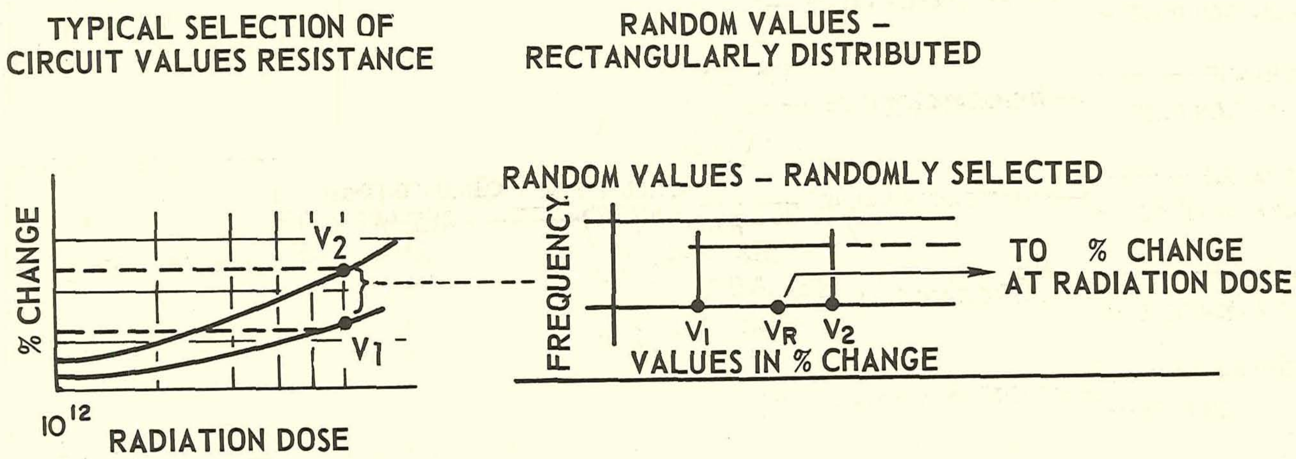
POWER FOR SPACE MISSIONS



1/18/62

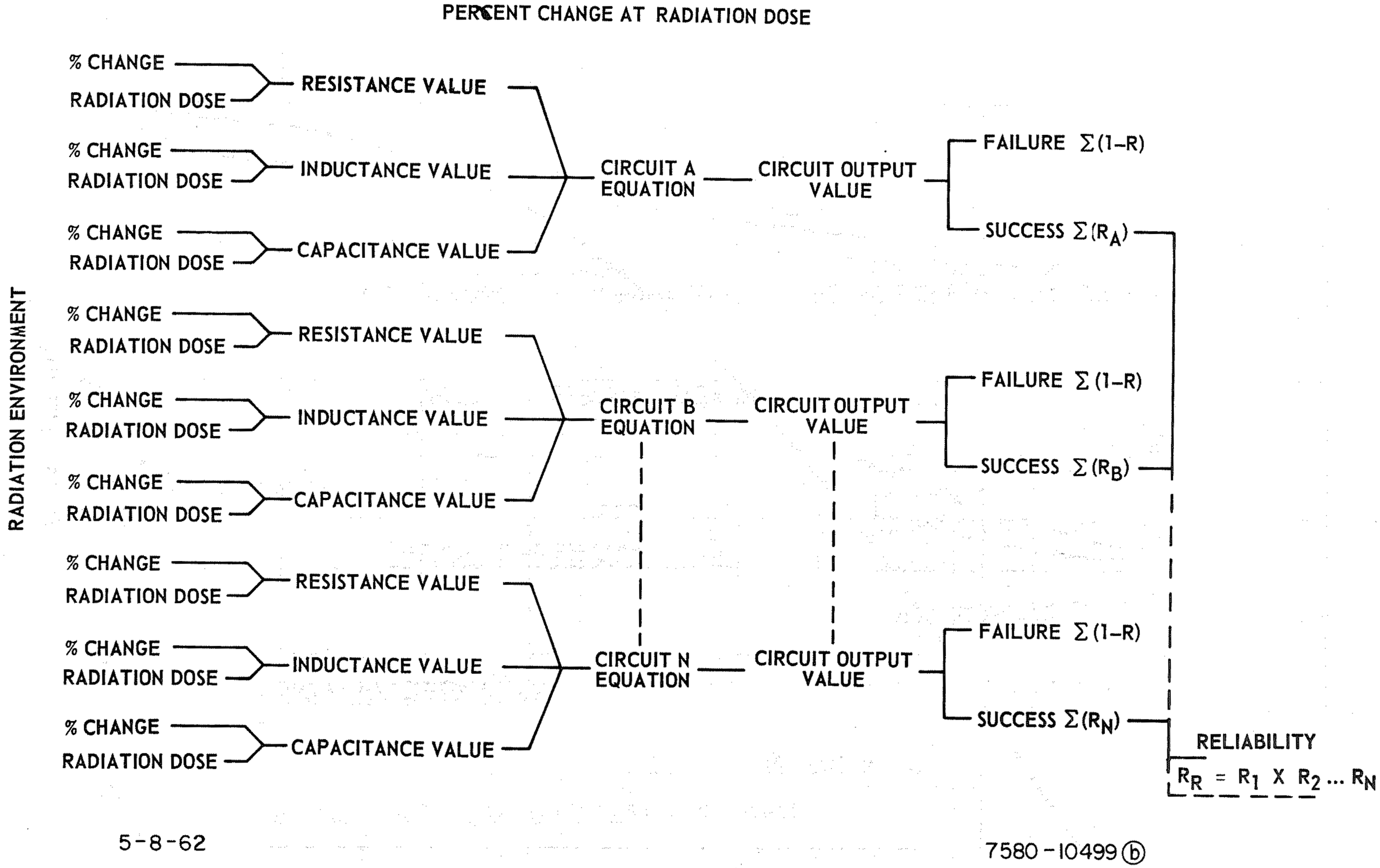
7590-1011


RELIABILITY APPROACH
$R_{STANDARD}$
STANDARD RELIABILITY ANALYSIS
$R_{RADIATION}$
REL_{RAD} RADIATION RELIABILITY ANALYSIS
$R_S X R_R$
TOTAL RELIABILITY ANALYSIS
5-8-62
7580-10499

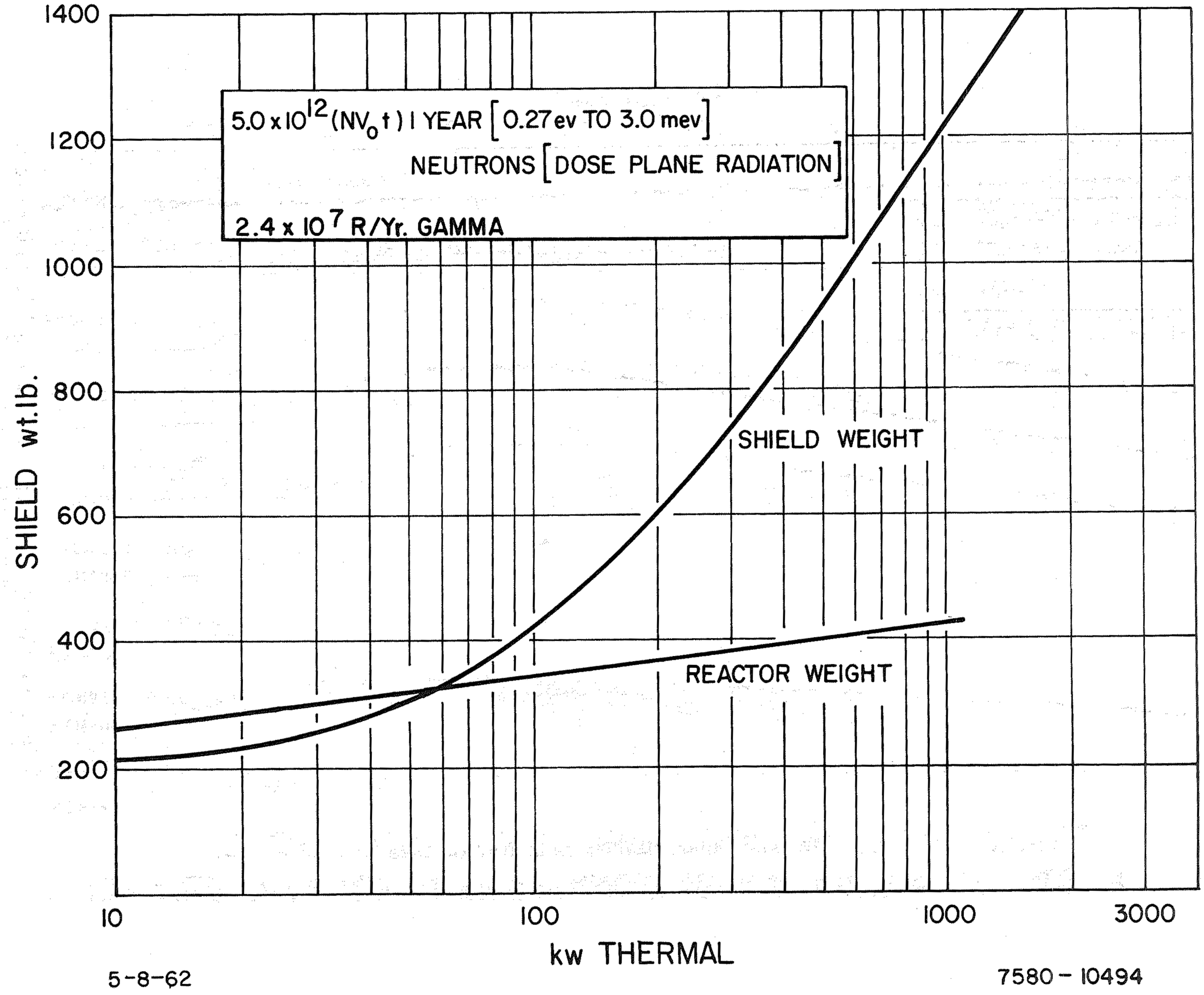


5-8-62

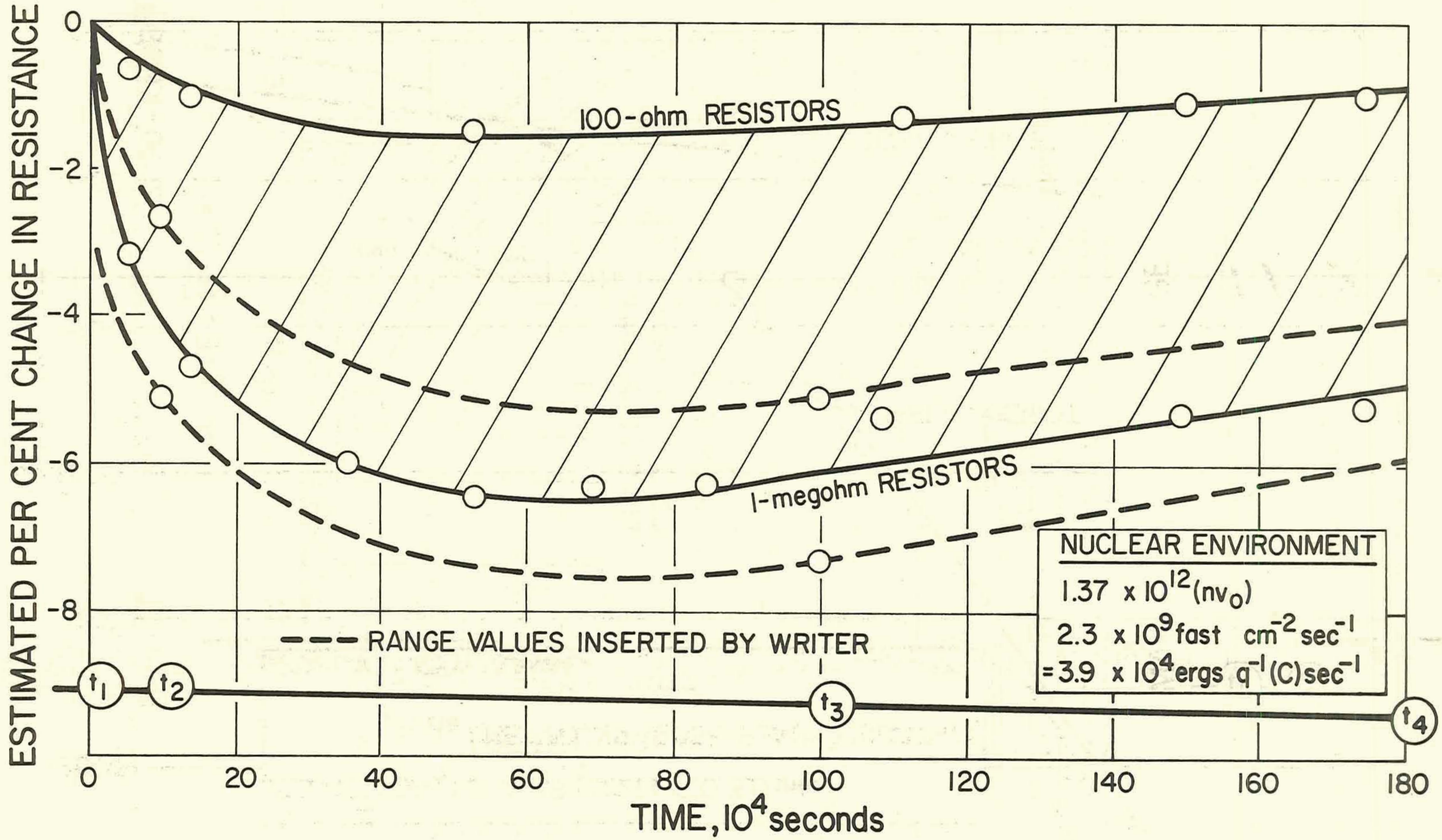
7580-10499 @


PERCENT CHANGE AT RADIATION DOSE
RADIATION ENVIRONMENT
% CHANGE
RADIATION DOSE
RESISTANCE VALUE
INDUCTANCE VALUE
CAPACITANCE VALUE
CIRCUIT A EQUATION
CIRCUIT B EQUATION
CIRCUIT N EQUATION
CIRCUIT OUTPUT VALUE
FAILURE Σ(1–R)
SUCCESS Σ(R_A)
SUCCESS Σ(R_B)
SUCCESS Σ(R_N)
RELIABILITY
R_R = R_1 X R_2 ... R_N
5-8-62
7580-10499 (b)

SHIELD & REACTOR GROWTH CURVES

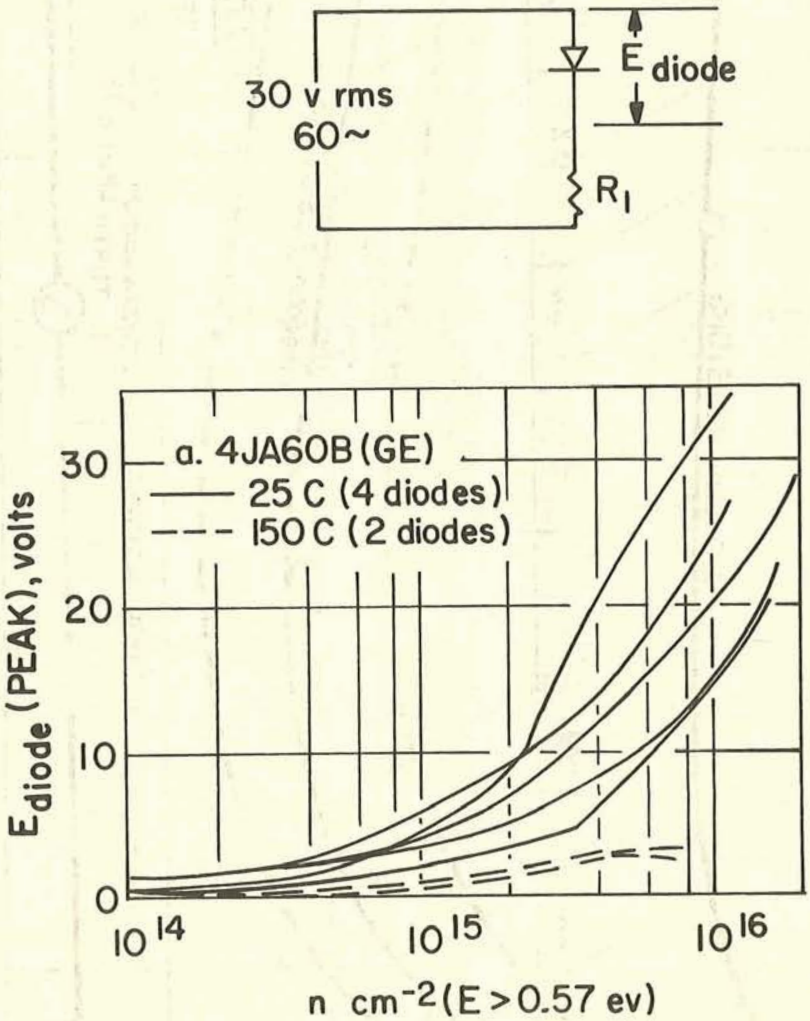


ESTIMATED CHANGES IN RESISTANCE AS A FUNCTION OF TIME FOR 100-TO 1,000,000 OHM CARBON COMPOSITION RESISTORS



5-8-62

7580-10497



5-8-62 7580-10498(a)

TABLE I

600°F COMPONENTS TEST (HOTELEC)							
TIME**/TEMP COMPONENT/CIRCUIT	0–500 HR AMB. ≈ 150°F	500–620 HR T = 200°F	620–812 HR T = 400°F	812–836 HR T = 600°F	836–884 T = 400°F	884–1316 HR AMB. ≈ 150°F	1316–1800 HR T = 300°F
TRIODES/ MULTIVIBRATOR (7625 GE)	*	*	*	CIRCUIT FAILED DUE TO CAPACITORS	PARTIAL RECOVERY	COMPLETE RECOVERY	*
TRIODES/FLIP FLOP (7625 GE)	*	*	*	CIRCUIT FAILED DUE TO DIODES	PARTIAL RECOVERY	COMPLETE RECOVERY	*
DIODES/FLIP FLOP (Z2689 GE)	*	*	*	INPUT DIODES DEVELOPED LOW RESISTANCE LEAKAGE EVIDENTLY THROUGH INSULATION, THUS RENDERING ENTIRE FLIP FLOP CIRCUIT INOPERATIVE. NO RECOVERY NOTED EVEN AT AMBIENT TEMPERATURE.			
DIODES/AND GATE (Z2689 GE)	FILAMENT POWER ONLY	FILAMENT POWER ONLY	FILAMENT POWER ONLY	THESE DIODES ALTHOUGH NOT ACTUALLY OPERATED EXCEPT FOR THE FILAMENTS SHOW THE SAME LOW RESISTANCE AS IDENTICAL TYPE IN THE FLIP FLOP.			
DIODE RECTIFIERS/ POWER SUPPLY (Z5365 GE)	BOTH OF THE GAS DIODES IN THIS FULL WAVE RECTIFIER FAILED BEFORE THE FURNANCE TEMPERATURE WAS RAISED AT ALL. THEY APPARENTLY FAILED THROUGH LOSS OF THEIR GAS.						
CAPACITORS/MULTI-VIBRATOR (BENDIX SCINTILLA E400 SERIES WOUND MICA PAPER)	*	*	*	FAILED DUE TO BREAKDOWN OF INSULATION RESISTANCE	PARTIAL RECOVERY	COMPLETE RECOVERY	OCCASIONAL ERRATIC OPERATION
RESISTORS/MULTI-VIBRATOR & FLIP FLOP	(PYRO-FILM UT501 CARBON FILM) (PYRO-FILM UT1001 CARBON FILM)		*	*	*	*	*
CAPACITORS/TESTED AS COMPONENTS (BENDIX E-400)	*		*	LEAKAGE RESISTANCE DECREASED BY 1/3	*	*	*
RESISTORS/TESTED AS COMPONENTS (SPRAGUE–KOOLOHM, PYROFILM–UT1001, & ROSENTHAL)	*	*	*	*	*	*	*

*NORMAL OPERATION
**TIME MEASURED FROM BEGINNING OF TEST, 11/9/61

5-8-62 7580-10495

TABLE II

SNAP TEST ENVIRONMENTS

ITEMS	VACUUM	TEMPERATURE	RADIATION	
			NEUTRONS DOSAGES	GAMMA RAYS
ELECTRICAL MATERIALS & COMPONENTS	10^{-6} mm Hg OR LESS	900°F → 1000°F	3.1×10^{19} $(n V_o t)$ FAST 3.6×10^{18} $(n V_o t)$ THERMAL	3.7×10^{10} R
ELECTRONIC COMPONENTS TRANSISTORS DIODES RESISTORS CAPACITORS MAGNETIC CORE	10^{-6} mm Hg OR LESS	<100°F	4.7×10^{12} $(n V_o t)$ FAST 1.0×10^{10} $(n V_o t)$ THERMAL	10^3 R/HR DOSE RATE

5-8-62

7580-10488

SIMULATED SAMPLING SCHEDULE

COMPONENT	t_1				t_2				t_3. . . . . . thru t_4
	RANDOM VALUES				RANDOM VALUES				
	SET 1	SET 2	SET 3	. . . . .SET 1000	SET 1	SET 2	SET 3	. . . . .SET 1000	
1. RESISTOR									
2. R. F. CHOKE									
3. CAPACITOR									
CIRCUIT OUTPUT RESPONSE	E_1	E_2	E_3	. . . . .E_{1000}					

TABLE III

5-8-62

7580-10493

TABLE IV

TIME	RESULTS		RANDOM FAILURE RATE/ADJUSTED R_r					
	SUCCESS 265V	FAILURE 220V	COMP 1	COMP 2	COMP 3	COMP 4	COMP N	TOTAL
t_1	986	14	XX	XX	XX	XX	XX	.XXX
t_2	992	8	XX	XX	XX	XX	XX	.XXX
t_3	957	43	XX	XX	XX	XX	XX	.XXX
t_4	980	20	XX	XX	XX	XX	XX	.XXX

5-8-62

7580-10492

TABLE V

STANDARDIZED TEST FORMAT | COMPONENT

		STANDARD ATMS PRESSURE									10^{-6} mm Hg PRESSURE									10^{-9} mm Hg → ETC.			
		TEMP 70°F			TEMP 200°F			TEMP 600°F			TEMP 70°F			TEMP 200°F			TEMP 600°F			TEMP. 70°F			
	$X\ 10^3$ SEC	100	100 K	1 MEG	100	100 K	1 MEG	100	100 K	1 MEG	100	100 K	1 MEG	100	100 K	1 MEG	100	100 K	1 MEG	100	100 K	1 MEG	
DOSE RATE 10^7	3.6	xx xx	xx xx	xx xx																			
	36																						
	360	xx xx	xx xx	xx xx																			
	3600					ISOLATION OF EFFECTS																	
	36000	xx xx	xx xx	xx xx		1. PRESSURE EFFECTS																	
DOSE RATE 10^9	3.6					2. TEMP EFFECTS																	
	36					3. RATING EFFECTS																	
	360					4. DOSE RATE EFFECTS																	
	3600					5. AND ALL INTERACTIONS																	
	36000																						
DOSE RATE 10^{11}	3.6					54/ BLOCK TEMP																	
	36					162/PRESSURE 648/TOTAL																	
	360																						
	3600																						
	36000																						

5-8-62

7580 - 10490

TABLE VI

RESISTORS

MFG	TYPE		RATING		
	DESCRIPTION	REMARKS	%	WATTS	R (VALUES)
XXX	CARBON COMPOSITION		10	½ → 1	10 Ω → 22 MEG
	CARBON COMPOSITION		5	½ → 1	10 Ω → 22 MEG
	WIRE WOUND		10	½ → 2	.27 Ω → 8200 Ω
	WIRE WOUND		5	½ → 2	.27 Ω → 8200 Ω
	MOLDED METAL FILM		1	½ → 2	30.1 → 1.5 MEG
	MOLDED DEPOSITED CARBON		1	¼ → 1	10 Ω → 2.49 MEG
	EPOXY DEPOSITED CARBON		1	½	10 Ω → 2.49 MEG
	WIRE WOUND	POWER	5	5–225	1 Ω → 250 K
	WIRE WOUND	CERAMIC	1	½ → 100	.1 Ω → 2.5 MEG
	CARBON FILM	GLASS	1	⅛ → ¼	10 Ω → 1. MEG
	CDM	MOLDED	1	⅛ → ½	10 Ω → 2.5 MEG
XXX	ETC	ETC	ETC	ETC	ETC

	TYPES OF COMPONENTS	
1.	RESISTORS	
2.	CAPACITORS	
3.	TRANSFORMERS	
4.	RELAYS	
5.	SOLENOIDS	
6.	MOTORS	
7.	SWITCHES	
8.	CONNECTORS	
9.	PLUGS & SOCKETS	
10.	WIRE	
11.	INSULATION	
12.	TUBES	
13.	SEMICONDUCTORS	
a.	TRANSISTORS	
b.	DIODES	
14.	THERMISTORS	
15.	AND OTHERS	

5-8-62

REDUNDANCY AS APPLIED TO ANALOG CIRCUITRY FOR PROJECT RELAY

E. L. Bolden
Radio Corporation of America
Camden, New Jersey

R. A. Smith
Radio Corporation of America
Astro-Electronics Division
Hightstown, New Jersey

Summary

17281

The use of redundancy in analog circuitry should be carefully weighed to determine the suitability of the level of application within a system. Criterias dictating this level are circuit unreliability, circuit criticality to system's operation, weight, space and cost. The use of redundancy, standby operating will result in larger net gains in reliability over the standby inoperative technique when automatic switching of the latter is required. When earth controlled switching is provided, the latter technique is desirable, especially at the function level. The incorporation of redundancy in Project Relay results in a predicted reliability of .9508 increasing the reliability by a factor of 1.5 over that of a non-redundant system.

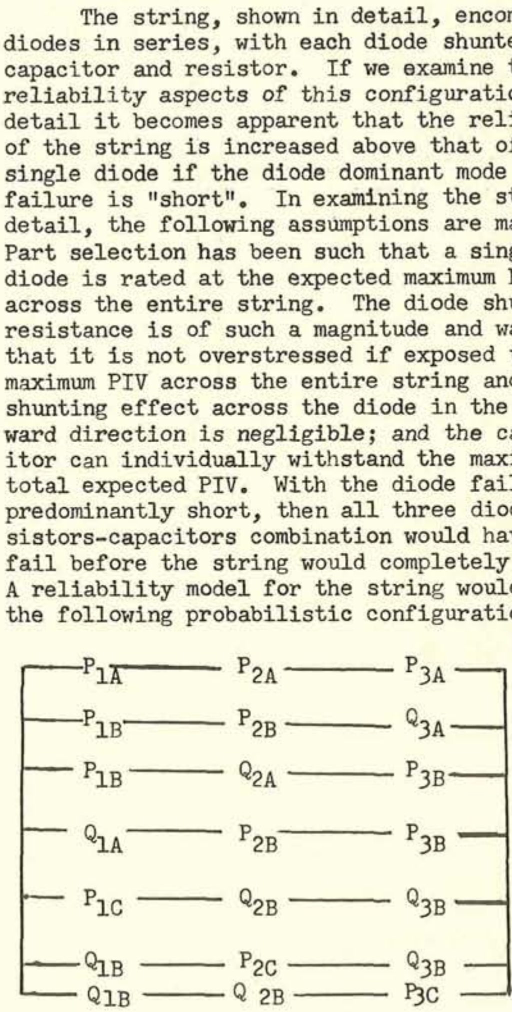
Introduction

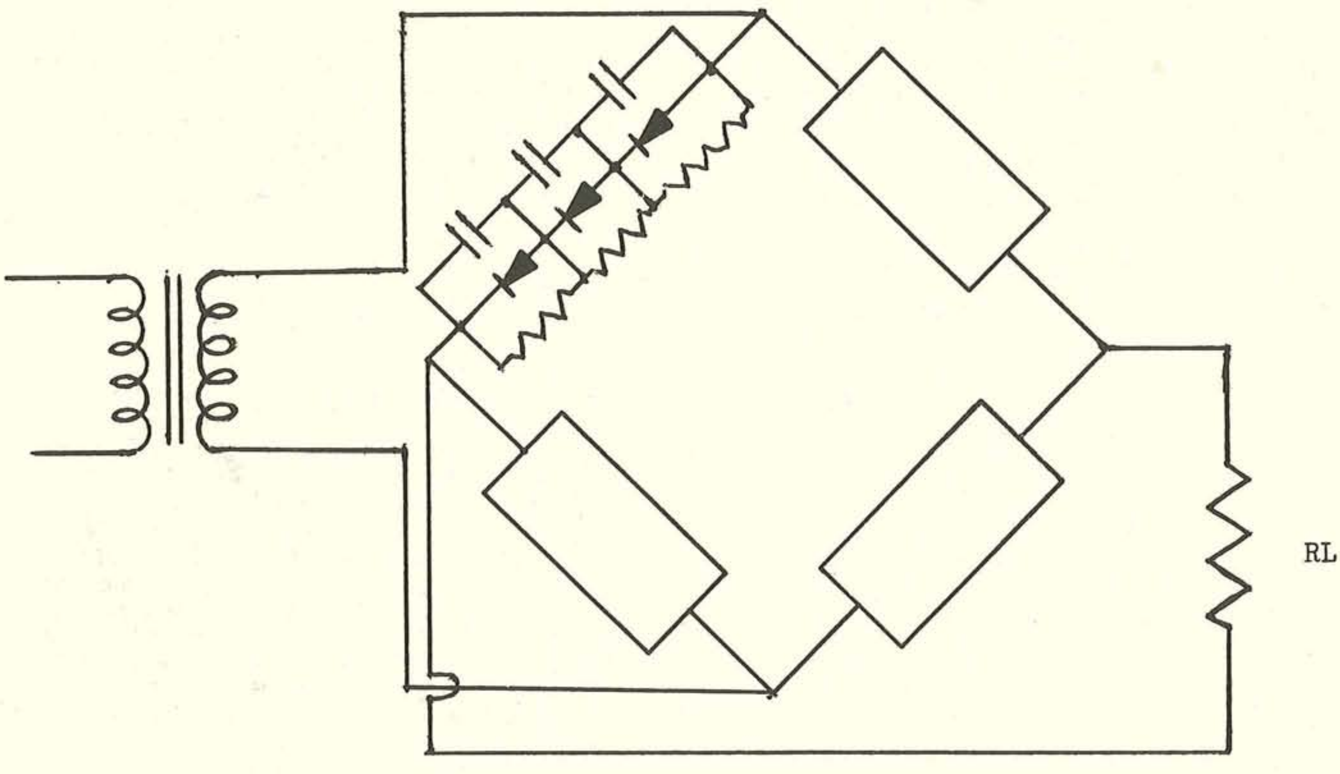
When it is required that a system be designed to a quantitative reliability figure, it is not enough that parts and stresses be kept to a minimum. During various stages of design, in a systems development, it frequently becomes apparent that reliability design goals must be met by means other than parts and electrical stress minimizing. Where such levels can not be met by minimizing techniques, then additional effort, usually through the use of redundancy, may achieve or surpass the required levels.

Redundancy when applied has as its objective the improvement of the systems reliability and effectiveness. If very high reliabilities are required, redundancy may encompass duplication, triplication, or an even higher usuage of parts, circuits or systems. The combination is not limited to merely duplication, that is, one out of two, or triplication, one out of three, but may be on a basis of two out of three, or three out of five, or whatever combination is most suitable for the particular situation at hand, This may apply at any system level. It may encompass whole systems or functions, circuits or even parts. Factors which will involve the level at which redundancy can best be applied are weight, electrical performance, matching, switching, sensing, and etc., as well as the actual gain in reliability that can be achieved.

Redundancy, when consideration is given to its application in analog circuitry, has as its goals the same objectives as when it is applied elsewhere. The actual application, however, may yield something more than the paralleling of functions, circuits, etc. For an illustration let us take one leg of the bridge rectifier of a power supply as shown in Figure 1.

The string, shown in detail, encompasses diodes in series, with each diode shunted by a capacitor and resistor. If we examine the reliability aspects of this configuration in detail it becomes apparent that the reliability of the string is increased above that of a single diode if the diode dominant mode of failure is "short". In examining the string in detail, the following assumptions are made. Part selection has been such that a single diode is rated at the expected maximum PIV across the entire string. The diode shunting resistance is of such a magnitude and wattage that it is not overstressed if exposed to the maximum PIV across the entire string and its shunting effect across the diode in the forward direction is negligible; and the capacitor can individually withstand the maximum total expected PIV. With the diode failing predominantly short, then all three diode-resistors-capacitors combination would have to fail before the string would completely fail. A reliability model for the string would show the following probabilistic configuration.




RL

Where P_{1A}, P_{2A}, and P_{3A} are the probabilities associated with all three surviving when all three are operable, Q_{1A}, Q_{2A} and Q_{3A} are the associated failure probabilities, P_{1B}, P_{2B}, and P_{3B} the probabilities associated with two surviving after one has failed. In the case of the diode string, the failure rate would change as failures occur. The individual diode combination failure rate increase would be a function of the inverse voltage and not the forward voltage since the forward dissipation or stress change during conduction would be negligible. For a single diode instead of the series diode combinations, the exponential failure law would apply.

That is

$$P_s = e^{-\lambda t}$$

The series combination, if non-redundant would still follow the exponential failure law. However, since there is redundancy, and although the individual parts still follow the exponential failure law, the resultant is not at all exponential in nature. It assumes a characteristic approaching that of a normal distribution. The probability of survival is given by the relation.

$$P_s = P_{1A}P_{2A}P_{3A} + P_{1B}\, P_{2B}\, Q_{3A} + P_{1B}\, P_{3B}\, Q_{2A} + P_{2B}\, P_{3B}\, Q_{1A} + P_{1C}\, Q_{2B}\, Q_{3B} + P_{2C}\, Q_{1B}\, Q_{3B} + P_{3C}\, Q_{1B}\, Q_{2B} \quad \text{or}$$

$$= e^{-(\lambda_{1A} + \lambda_{2B} + \lambda_{3A})t} + e^{-(\lambda_{1B} + \lambda_{2B})t}(1-e^{-\lambda_{3A}t}) + e^{-(\lambda_{1B} + \lambda_{3B})t}(1-e^{-\lambda_{2A}t}) + e^{-(\lambda_{2B} + \lambda_{3B})t}(1-e^{-\lambda_{1A}t})$$

$$+ (1-e^{-\lambda_{2B}t})(1-e^{\lambda_{3B}t})\, e^{-\lambda_{1C}t} + (1-e^{-\lambda_{1B}t})(1-e^{-\lambda_{3B}t})\, e^{-\lambda_{2C}t} + (1-e^{-\lambda_{1B}t})(1-e^{-\lambda_{2B}t})(e^{-\lambda_{3C}t}).$$

It is apparent from this illustration that reliability can be enhanced by this arrangement. In the illustration the subnumerics 1A, 2A, and 3A refer to the probability and failure rates when all three diode combinations are operable; 1B, 2B, and 3B refer to the probability and failure rates when two out of three are operable; and 1C, 2C, and 3C refer to the probability and failure rates when one out of three is operable. If we assume for illustrative purposes that a single diode has a P_s, for time t, of 0.9, and again assume a P_s for the diode-resistor-combination of 0.85 when all three are operable, 0.80 when only two are operable and 0.75 when only one is operable, the P_s of the string of three is 0.974. The reliability improvement is evident even though the levels of P_s are pessimistic, as compared with the 0.9 figure for the single diode. In practice, the P_s of the parallel combination of each series element would be very nearly the same as the individual diode. The subsequent string improvement is then immediately apparent.

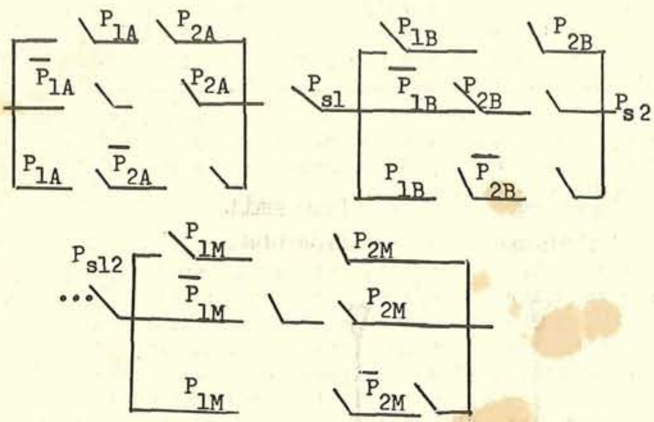
The use of circuit redundancy, from the reliability standpoint, has two criterias for review prior to application. The unreliability of the circuit under consideration should be considerably worse than the remaining associated circuits of an equipment or a system's function and/or the circuit's criticality to the system's effectiveness should be at a high level. The reduction of part application levels and improved component part reliability have a tendency to keep the unreliability of all circuit types fairly equal and has a tendency to negate the first criteria. However, the circuit's criticality (defined here as the degree of curtailment of the system's operational output resulting from the circuit failing) is usually very evident and can be realistically coped with. An example of this circuit redundancy is discussed later in the command control circuitry.

The next area of redundancy is at the function or equipment level. Here, the criteria for use depends on the equality of the unreliability of the individual circuits, the cost of isolation and combining for circuit redundancy vs equipment redundancy, and the effect on weight and space. As an illustration of this application, the receiver from the command control circuitry will be used.

Because of the derating policies envoked on parts application and since part complexity levels are nearly identical, the unreliability of the circuits are very nearly equal (in this example approximately 0.00111). The addition of a redundant circuit would in effect reduce the unreliability associated with a one out of two situation, by a factor of 1000 or if discussion is translated into terms of an effective failure rate it would change from 0.154 %/1000 hrs. to 0.00154 %/1000 hrs. However, to accomplish such an arrangement, isolation and combining circuits would have to be incorporated, as a minimal effort, to have continuity of operation.

The cost of isolation and combining would be a minimum failure rate of 0.020 %/1000 hrs. (assuming a single diode would accomplish these functions). Since thirteen (13) circuits are involved, it would require at least twelve (12) such networks all which would

have to be considered as series reliability elements. The reliability of such a configuration would be depicted by the following:



where the subscripts A thru M represent circuit stages, the subcripts 1 and 2 represent the redundancy of each stage, the subscript sl thru sl2 represents the isolation and combining stages.

The reliability of the command receiver then is bounded by a maximum value associated with these isolation and combining circuits and approaches 0.9983.

If two receivers are operated in parallel redundancy, isolation is required at the inputs and isolation and combining may be required at the output. The input isolation will not require any electrical component parts but could be either coaxial in nature or a printed circuit. Either one will exhibit a negligible failure rate contribution. However, the isolation and combining of the output may contribute a failure rate of 0.040 %/1000 hrs. The overall reliability of this configuration will involve the product of the redundant receivers reliability (0.999893 based on a failure rate 2.012 %/1000 hrs/each) and the isolation and combining reliability (0.99972) giving a value of 0.999613 as opposed to 0.9983 for the circuit redundant condition.

Such are the redundancy techniques applied to analog circuitry of the NASA Relay spacecraft electrical system design. The areas of application are discussed in the subsequent paragraphs.

NASA's Relay

The system described is NASA's Relay, being designed and fabricated by the Astro-Electronics Division of RCA. For the purpose of this paper, it has been broken down into four major areas; a) the system power supply; b) the wide-band repeaters, c) the command control circuitry; and d) the telemetry circuitry. Each area will be broken down to illustrate the redundancy incorporated in the design and the effects of this redundancy on reliability numerics.

System Power Supply

Solar Cells and Diodes - Conversion solar energy to electrical energy.

Voltage Limiter - Limit voltage to voltage regulators for satisfactory regulation.

Charge Controller and Limiter - For limiting charging-discharge rate to batteries.

Voltage Regulators (High and Low Power)- Tight voltage control for critical circuits.

Batteries - Storage for peak power requirements.

Wideband Repeaters

Receiver - Receives 1725 MCS amplifies and converts to 4170 MC for drive power to TWT Amplifier. Contains both wideband and narrowband circuits to accomodate television and telephone signals, respectively. Also includes a 4080 beacon to aid in ground tracking of the wideband antenna.

T.W.T Amplifier - Power Amplifier 4050-4250 MCS 11 watts output, 33db gain at 5.5 mw input from receiver.

T.W.T Power Supply - Voltage developed for the T.W.T Amplifier.

Command Control Circuitry

Command Receiver - Reception of VHF signal for commands translate to an audio output.

Demodulator - Detection of pulse-duration-modulated 5.451 KC tone and regenerate a noise-free PDM signal.

Decoder - Translates PDM pulses into "0", "1", and sync pulses which operate a magnetic shift register decoder providing 20 output commands.

Control Box - Accepts decoded commands and performs the function.

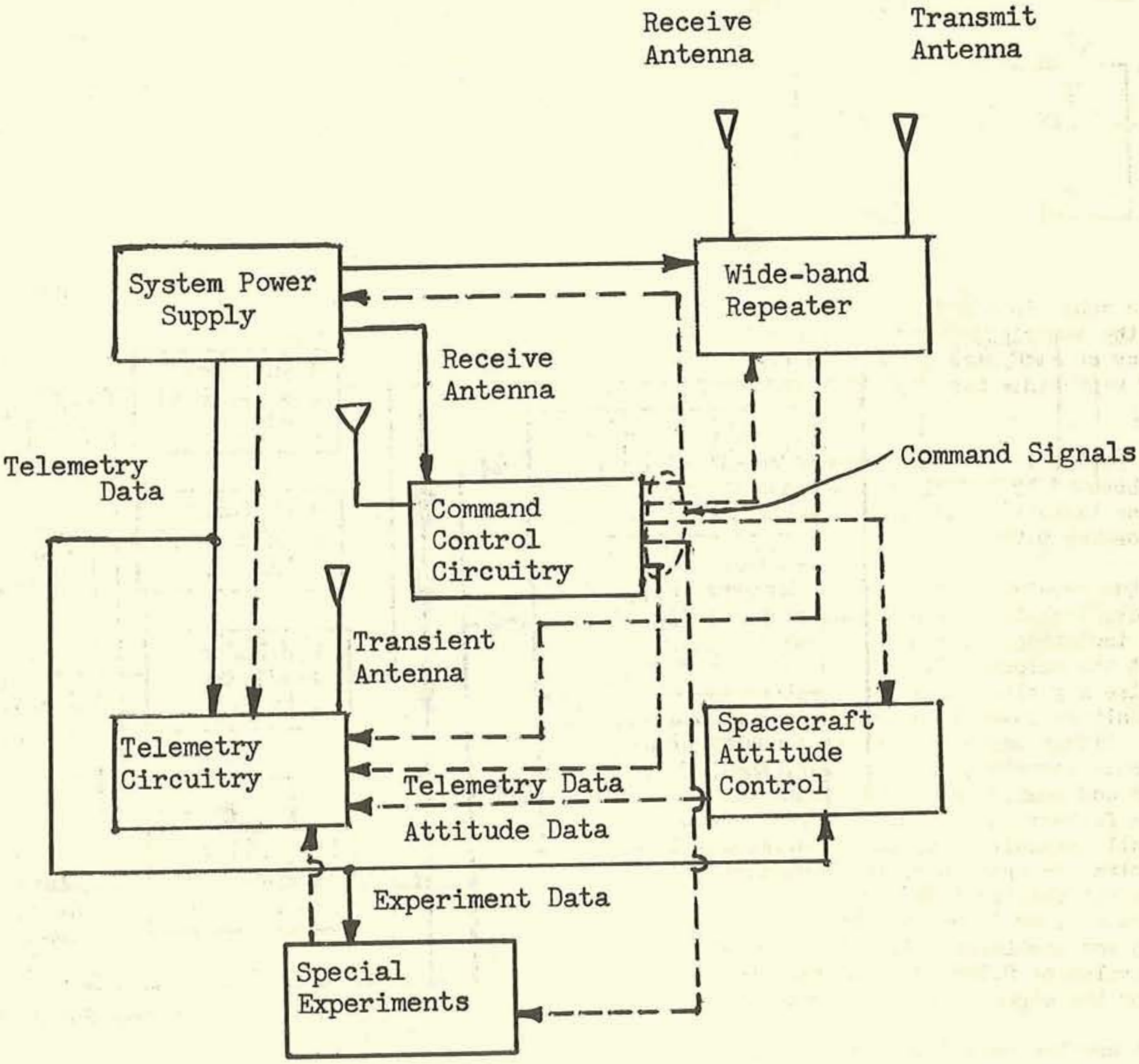
Telemetry Circuitry

Encoder - Acceptance of telemetry and special experiment data conversion into digital data for transmission.

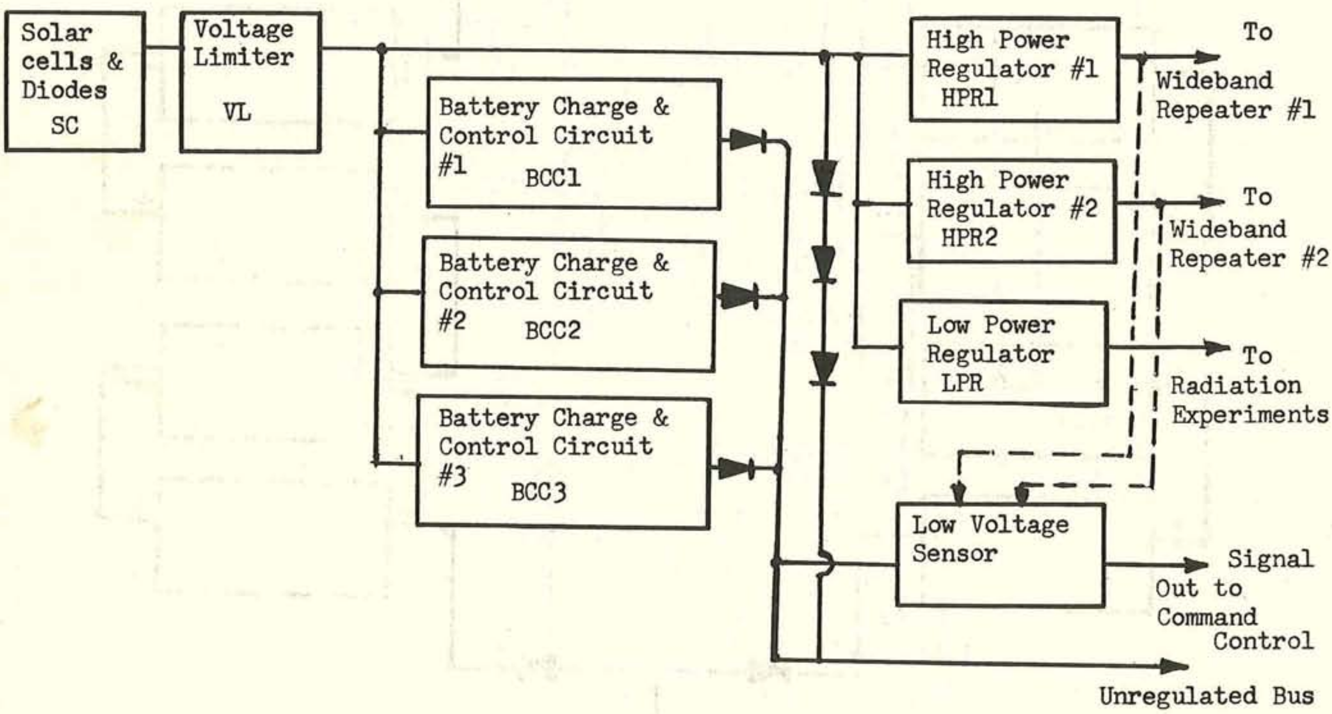
Transmitter - Provided necessary RF power for tracking and transmission of encoder or horizon scanner data.

Modulator Switch - Acceptance of horizon scanner FM subcarrier or encoder output for modulating transmitter RF power.

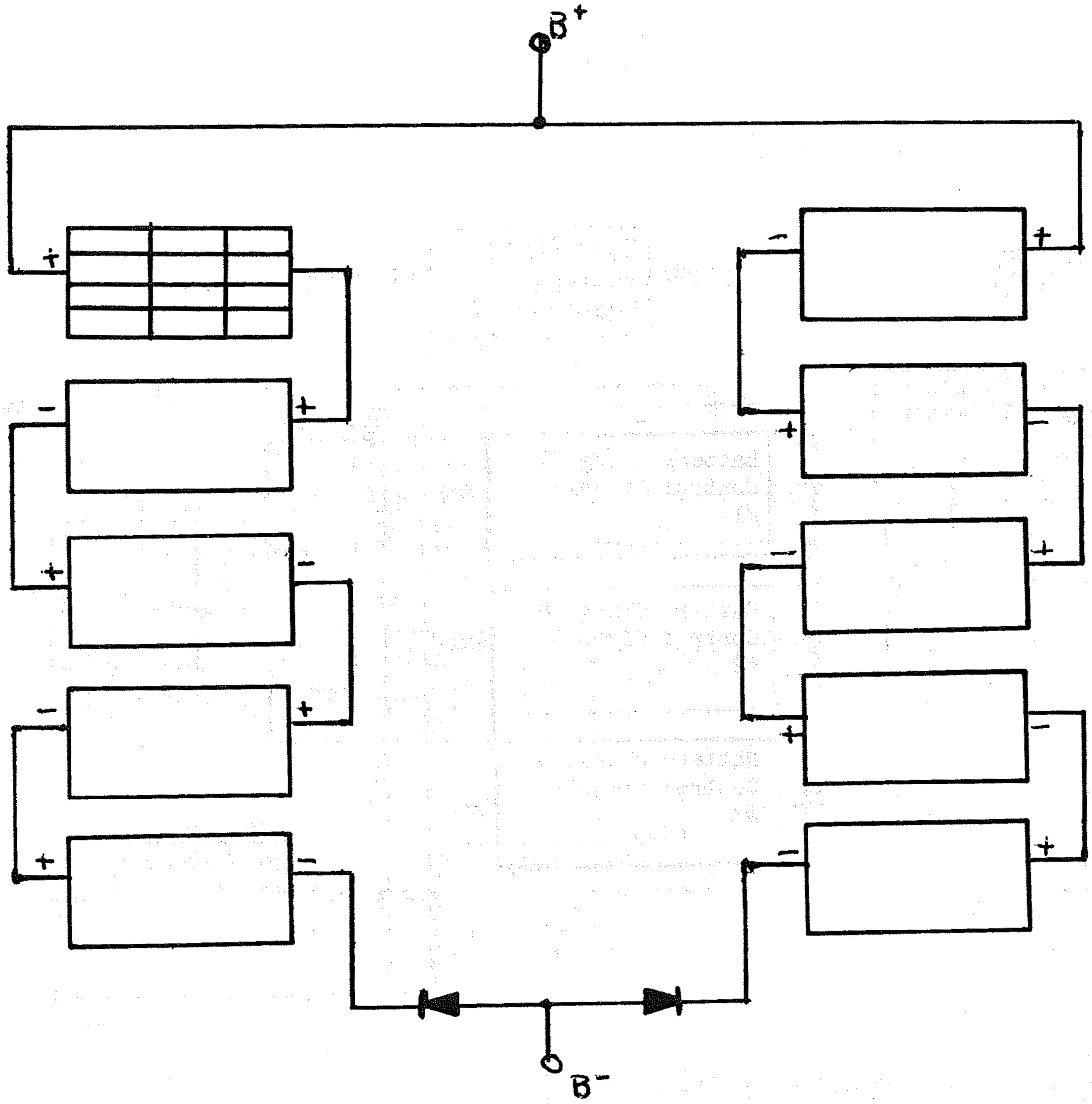
Horizon Scanner - Provide pulse data for


Receive Antenna
Transmit Antenna
System Power Supply
Wide-band Repeater
Receive Antenna
Command Signals
Telemetry Data
Command Control Circuitry
Transient Antenna
Telemetry Circuitry
Telemetry Data
Attitude Data
Spacecraft Attitude Control
Experiment Data
Special Experiments

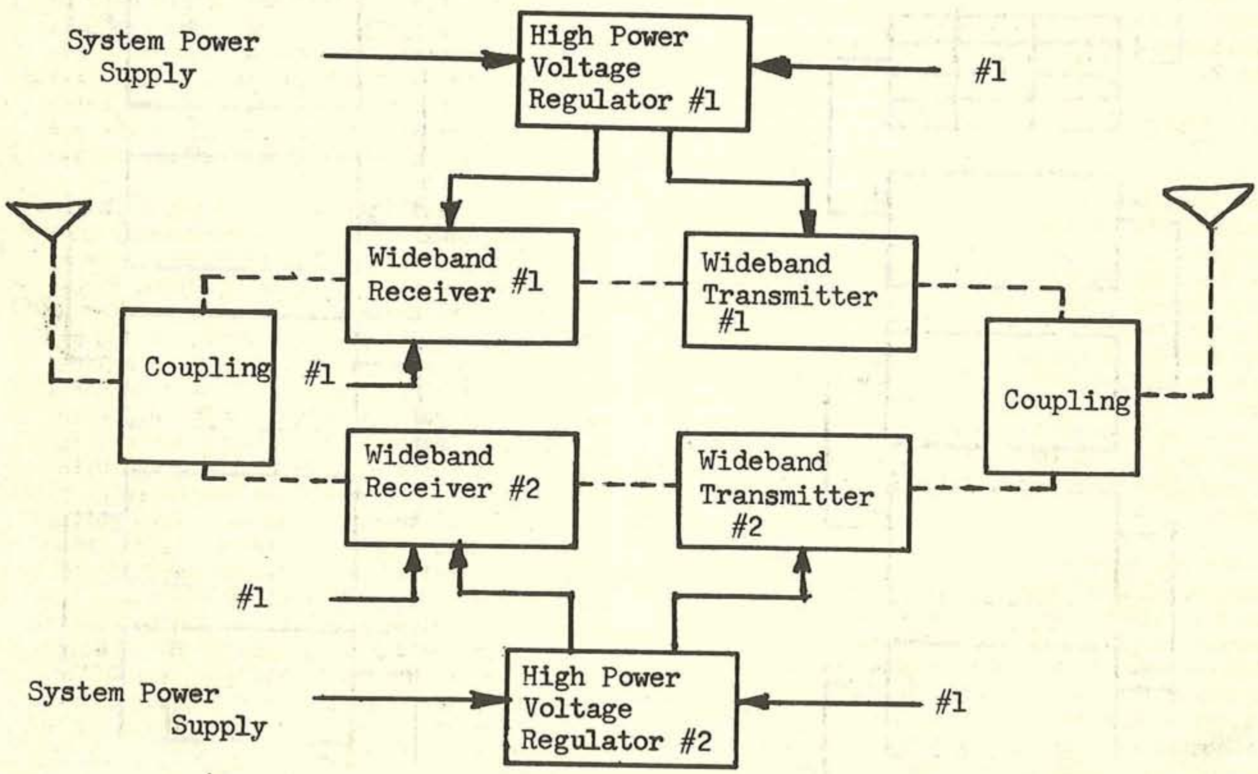
NASA's Relay



System Power Supply



Solar Panel Interconnections



#1 Inputs for command functions from Command Control Box output channels.

Wide-band Repeater

indication of spacecraft attitude to horizon.

Sun Sensor (GFE) - Provide output pulse indicating attitude to sun.

Magnetic Torque Coil - When provided with current flow develop magnetic field for attitude control.

Precession Damper - Provide dampening to prevent tumbling of spacecraft in orbit.

The equipment listed above when integrated into a system is capable of receiving and retransmitting either video information and voice in one direction or two-way voice by the wideband subsystem and telemetry, special experiment and attitude control data by the telemetry subsystem. The block diagram illustrating systems operation is shown as Figure 2.

Systems Power Supply

Figure 3 illustrates the block diagram of the systems power supply. Four areas of redundancy are incorporated in this design; the solar cells, the battery charge and control, the high power regulators and the low voltage sensor. There are two power output points provided for the equipment. The regulated output is fed by both the solar cells and the battery sources. Whereas the unregulated output is fed nominally from the battery sources alone. However, when the battery voltage is low an emergency path has been provided between the first and second outputs.

For redundancy in the solar cell area, a series-parallel wiring scheme allows failures to occur, either shorts or opens, without seriously jeopardizing the capability of providing the necessary system power. Figure 4 illustrates the inter-connection wiring of these cells on a panel basis. Normally three (3) elements of four (4) parallel cells are connected in series in each block of cells.

There are five (5) blocks of cells for each leg and fifteen (15) legs on the solar cell system. The following numerical calculations shows the benefit of using such a design. Looking at Figure 4, to a cell block, the loss of any individual cell can have one of two effects. If the cell shorts then the voltage contribution of that cell block is lost. If the cell opens the current contribution of that cell is lost. Since the system configuration delivers a nominal 35 volts when only 28 volts is required, the voltage loss will be insignificant and will remain insignificant due to the parallel legs. Likewise the current contribution will, if an open occurs, be lost but since a maximum loss of power from 2050 cells can be accepted, the eighty cells that are being treated are likewise insignificant to the system. Acceptable system operation then is defined as only one failure per cell block will be acceptable for satisfactory operation. On the basis of this, then eleven (11) out of twelve (12) cells in every block must survive the operational mode. This can be adequately described by the binomial expression

$$P_s = p^{12}\ q^0 + 12p^{11}\ q^1$$

or $0.998128 + 0.001584 = 0.999712$ where P_s of each solar cell is 0.99825.

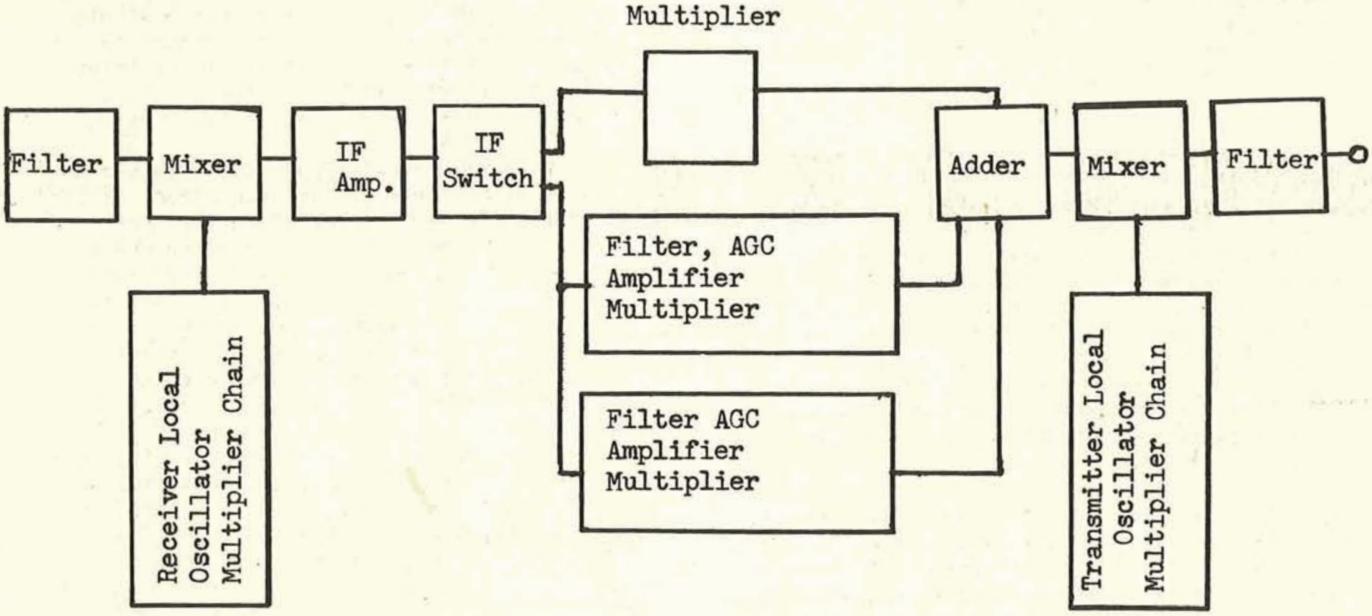
Now consider the design to incorporate no additional power delivery capabilities but designed to provide the exact power requirements. The failure then of any cell begins to reduce the current delivery capabilities. Under these conditions, then a single failure would be classified as a system failure and the probability of survival of the solar cells would be directly reflected by the summation of the individual cell failure rates.

The second area of redundancy is a complete functional one for one redundancy in the battery charge and control circuitry. Here three (3) circuits have been provided where any two of the three will provide sufficient operation provided the spacecraft is not required to operate extensively during a dark period. The circuitry consist of a comparator and series regulator network which controls the charging rate to the battery packs. When the battery voltage is 25 or above and with normal input voltage applied the charging rate is between 0.5 to 0.65 amperes. With voltage under 25 volts and normal input the charging rate is controlled to a trickle rate of .05 to .07 amperes. Since two out of three are necessary, a direct comparison can be made to indicate the reliability gain of this redundancy. Again the applicable expression for determining the numerics is the binomial expression which gives a value for the 2 out of 3 condition of 0.9993 and the value of 0.9854 for 2 out of 2.

The final point of redundancy in the system power supply consists of two high power voltage regulators, one each for the wide-band repeater stages. This is not a one for one redundancy but each regulator is a series element in the repeater stages where complete subsystems are provided on a one to one basis. This is illustrated in Figure 5.

Wide-band Repeaters

The wide-band repeater is a complete subsystem composed of the receiver and the high power transmitter for handling either TV tranmission between continents or for handling two way voice or telegraphy transmission. Figure 5 shows the system operation-



Wideband Receiver

al block diagram illustrating the complete one for one redundancy on a subsystem basis. It is controlled in such a manner that any short occurring after the series regulator network can be eliminated by an off-command.

Other redundancy aspects are in evidence in the wideband receiver (see Figure 6). An IF switch in the receiver allows the unit to process either the single way TV and voice transmission or the two way voice. The two receivers provide, from the IF switch to the adder circuit, additional reduced modes of operation. The probability of having at least single way TV and voice transmission or two way voice transmission is associated with having 1 out of 4 of these circuits working plus the remaining portions of the receiver as series elements. The possibility of having both single way TV and voice transmission and two way voice transmission become 1 out of 2 for each type of circuit plus the remaining portions of the receiver as series elements.

One other area of part redundancy is incorporated in the TWT power supply high voltage rectifier elements. Here the rectifier diodes were purchased in such a manner to obtain additional series diodes for redundancy.

The high-voltage diode rectifiers are composed of series elements to withstand the peak inverse voltages of such circuits. In order to assure adequate performance from these units, the higher PIV rated units have been used. The units selected are rated at 4000 and 5000 PIV. To obtain a realistic failure rate for these diodes, the effect of the redundant series elements was considered. Analyzing the smaller, 4000 volt unit, there are ten diodes in the series string, each rated at 400 PIV. The operating reverse voltage of the circuit involved is 1650 volts, which requires only 5 series elements. The second five are redundant. However, to keep a voltage derating factor on the PIV, seven diodes are considered to be required. Then three (3) diodes can fail due to shorting, without reducing the peak inverse capabilities to the derating level. The reliability then can be described in terms of the probability that three of the series elements will fail. This is described by the sum of the probabilities of 0, 1, 2, or 3 failures occurring and can be calculated by using the binomial expression. If it is assumed that the probability of failure for each diode remains the same, then the total probability of getting three or less failures is 0.99977. Then the effective failure rate associated with each leg of the rectifier circuit is .0026 %/1000 hrs. or 0.003 percent. This is the failure rate used to describe the redundant diodes.

Command Control Circuitry

The command control is a complete subsystem of Project RELAY whose function is the reception, demodulation, and decoding of command signals. This is accomplished in the block diagram shown in Figure 7. This diagram is a complete two-redundant configuration of the subsystem utilized in this project. The redundancy utilized is standby active. Though the basic reliability gain is less than that with standby inactive, the net gain is greater since the standby active negates the need for sensing and switching and their additional unreliabilities as would be required in a standby inactive redundancy configuration.

For reliability comparison purposes a non-redundant subsystem is shown in Figure 8. Utilizing the same functional building block as in the two-redundant configuration, the reliability gain or reduction of unreliability can be easily ascertained.

Consider first the block diagram of Figure 8. From this figure, the reliability diagram of Figure 9 has been constructed. In this configuration, the reliability of the subsystem is dependent upon the product of the individual function reliabilities. Thus, for this configuration, the reliability is no better than the most unreliable function and is substantially less than this in practice since no function has a reliability of unity. The subsystem mathematical model takes on the form

$$P_{\substack{\text{Non-Redundant}\\ \text{Command Control}}} = P(t)_{RF} \cdot P(t)_{L.O.} \cdot P(t)_{Mixer} \cdot$$

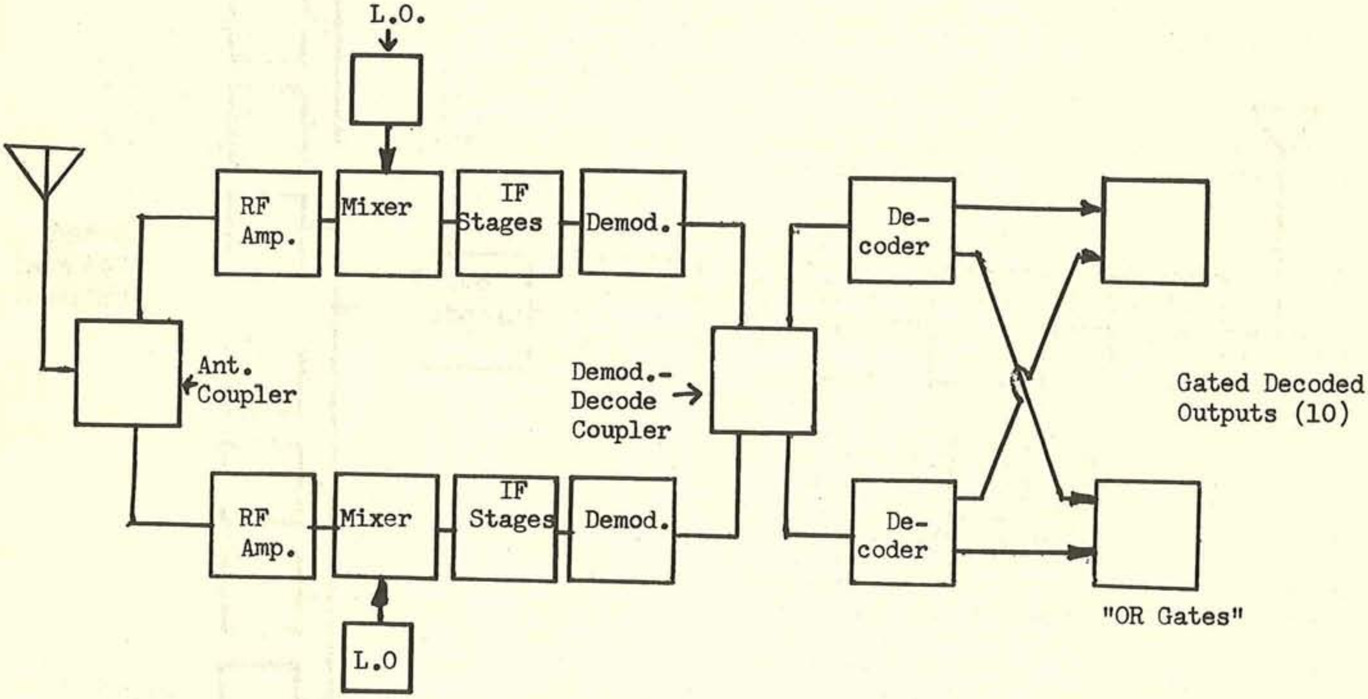
$$P(t)_{\text{IF Strip}} \cdot P(t)_{\text{Demodulator}} \cdot P(t)_{\text{Decoder}}$$

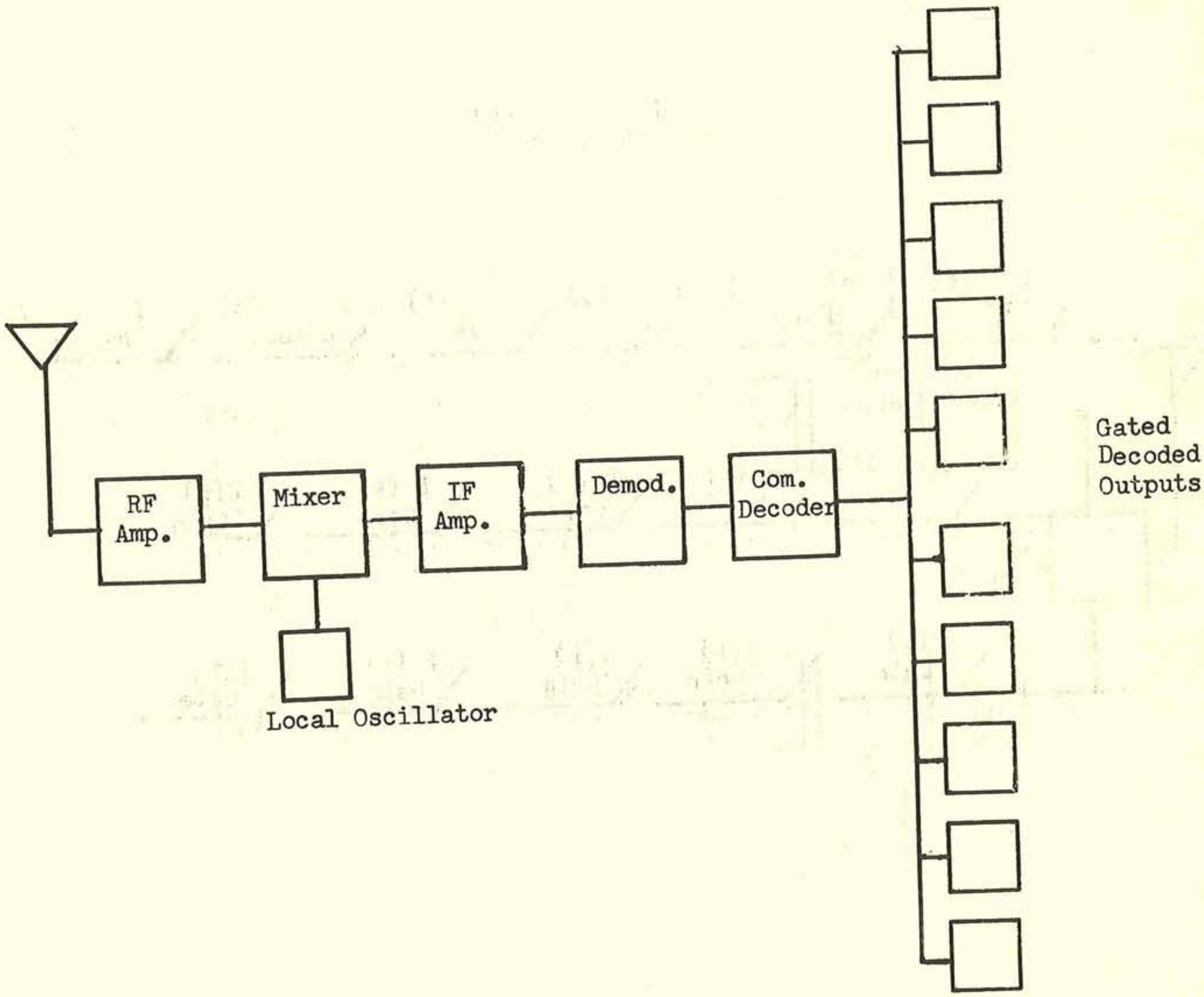
where $P_{RF}(t) \cdot P_{L.O}(t) \cdot P_{Mixer}(t) \cdot P(t)_{\text{IF Strip}} =$

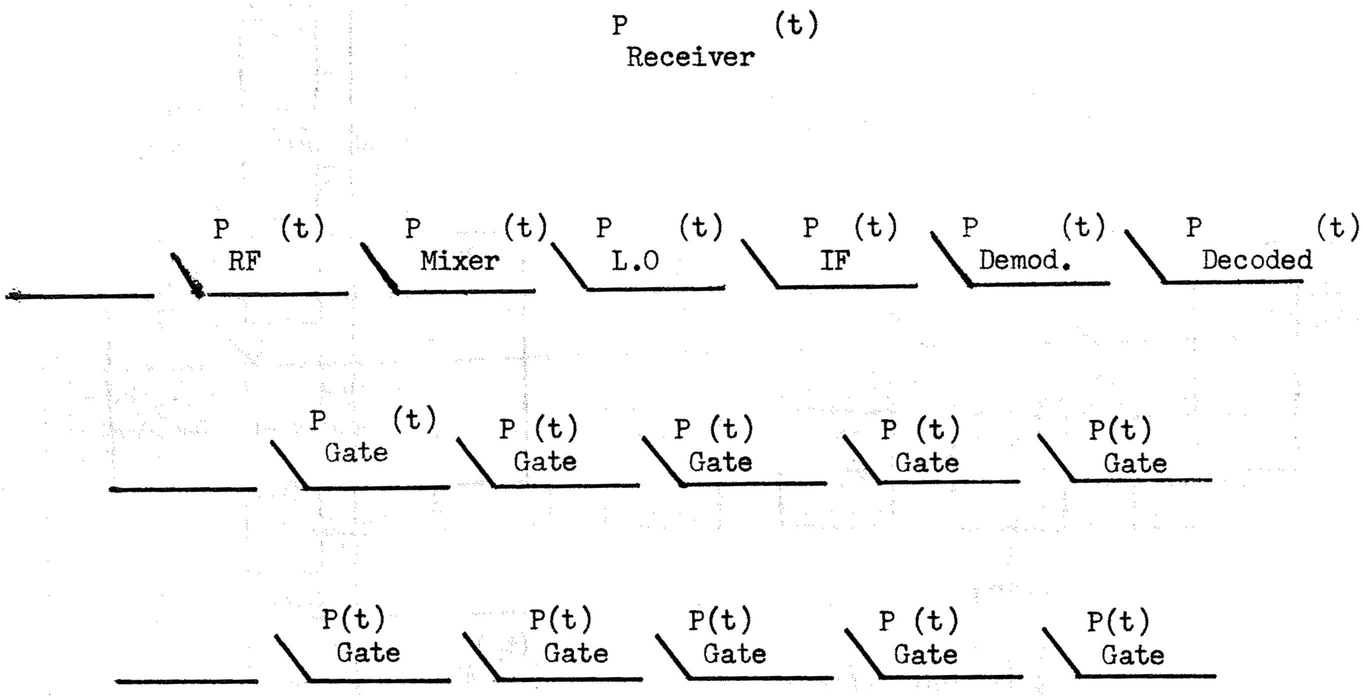
$$P(t)_{Rcvr}$$

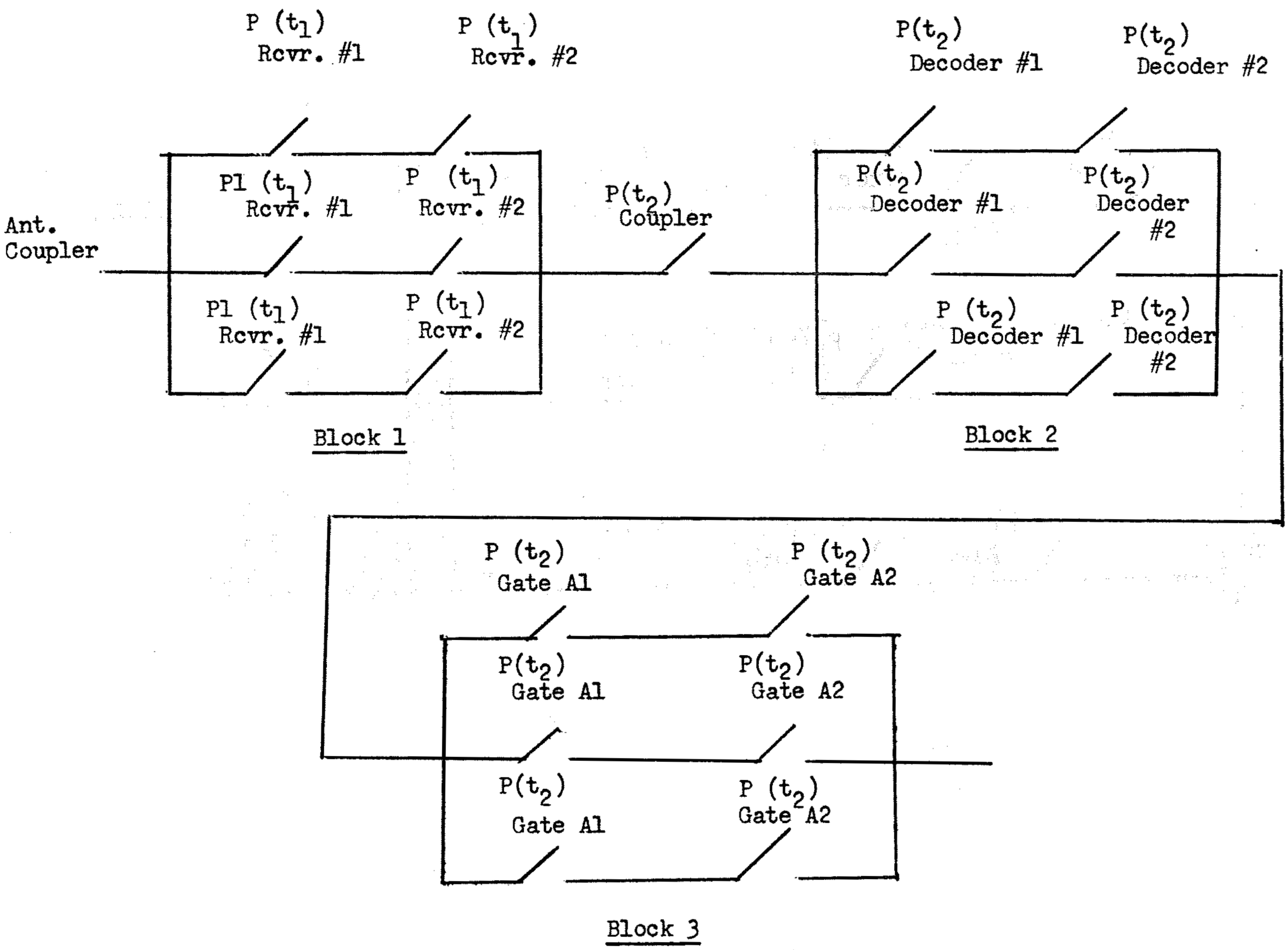
The probabilities of survival for 30 days (t_1 = 720 hours) were determined for those control functions required to operate continuously. These are shown where t_1 appears as the independent variable. For those functions on a cyclic basis, a 10% duty factor has been estimated as being applicable. Those functions are shown by the time function t_2. Thus $t_2 = t_1/10$.

The non-redundant control configuration utilized these times. The probability of survival for the command control receiver function up to and including the IF stages was estimated at 99.79% for 30 days. The demodulator function was estimated at 98.60% probability of survival for 30 days and the decoder at 97.21% for 30 days at the 10% duty factor. The probability of survival of the non-redundant command control through the decoder function (not including "OR gates") then is 95.588%.

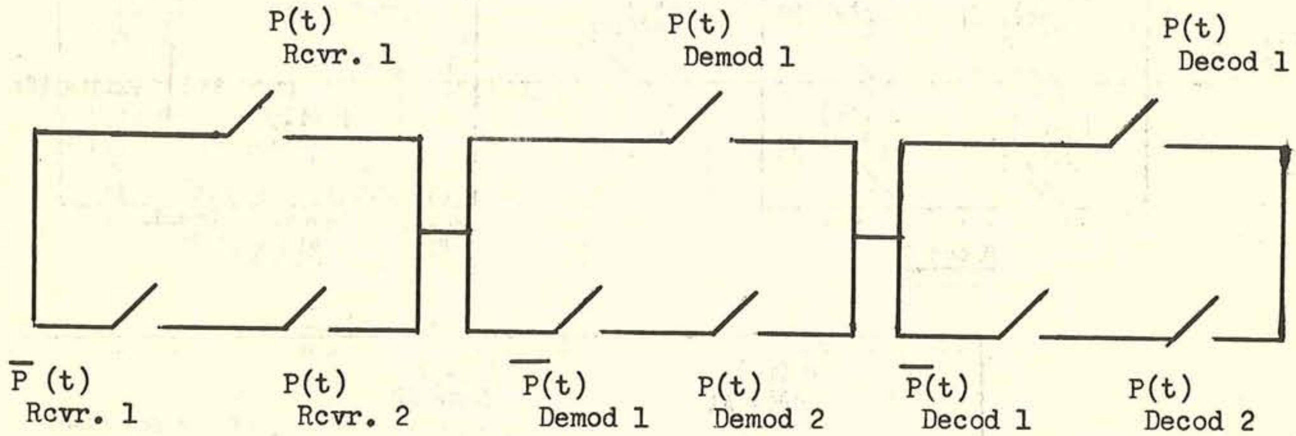

L.O.
RF Amp.
Mixer
IF Stages
Demod.
De-coder
Ant. Coupler
Demod.-Decode Coupler
Gated Decoded Outputs (10)
RF Amp.
Mixer
IF Stages
Demod.
De-coder
"OR Gates"
L.O


RF Amp.
Mixer
IF Amp.
Demod.
Com. Decoder
Local Oscillator
Gated Decoded Outputs


$P_{Receiver}(t)$
$P_{RF}(t)$
$P_{Mixer}(t)$
$P_{L.O}(t)$
$P_{IF}(t)$
$P_{Demod.}(t)$
$P_{Decoded}(t)$
$P_{Gate}(t)$
$P(t)$ Gate
$P(t)$ Gate
$P(t)$ Gate
$P(t)$ Gate
$P(t)$ Gate
$P(t)$ Gate
$P(t)$ Gate
$P(t)$ Gate
$P(t)$ Gate



Block 3 represents the input gates to a single command channel. Ten such elements are required for completing the reliability diagram.


P(t)
Rcvr. 1
P(t)
Demod 1
P(t)
Decod 1
$\overline{P}$ (t)
Rcvr. 1
P(t)
Rcvr. 2
$\overline{P}$(t)
Demod 1
P(t)
Demod 2
$\overline{P}$(t)
Decod 1
P(t)
Decod 2

Consider now the command control subsystem, the two redundant configuration, as depicted in Figure 7. This subsystem incorporates redundant receive and demodulate functions and redundant decode functions. Also each of the ten decoded outputs is channeled through a redundant pair of "OR gates". The reliability diagram for this subsystem is shown in Figure 10. In order to eliminate sensing and switching functions that are generally necessary for redundant configuration, an antenna coupler has been utilized to isolate the inputs from each other, yet allow each receiver to be indepently operable from a common antenna. The demodulated receiver outputs are fed through appropriate isolation to both decoders giving a both-either-or redundant arrangement. Similarly, the decoded outputs are also both-either-or through paired OR gates. With this arrangement, all functions operate simultaneously and there exists no requirement for sensing or switching. A failure along one channel or leg is not reflected into the system because of the unidirectional characteristics of the various forms of isolation.

From the reliability diagram in Figure 10, the mathematical model takes on the form (not including the redundant OR gates):

$$P(t)_{\substack{\text{Redundant} \\ \text{Command Rcvr.}}} = P(t_1)_{\substack{\text{Ant.} \\ \text{Cpl.}}} \cdot \left[1-(1-P(t_1)_{\substack{\text{Rcvr} \\ \#1}}\ (1-P(t_1))_{\substack{\text{Rcvr} \\ \#2}}\right]$$

$$\cdot \left[1-(1-P(t_2)_{\substack{\text{Decoder} \\ \#1}} \cdot 1-P(t_2))_{\substack{\text{Decoder} \\ \#2}}\right] \cdot$$

$$P(t_2)_{\substack{\text{Coupler} \\ \text{(demod-} \\ \text{decode)}}}$$

The probability of survival of the redundant configuration yields a probability of approximately 99.86%. This consists of $(1-4.41 \times 10^{-6}) \times 100\%$ for the redundant receiver portion, 99.92% for the redundant decoder portion and 99.94% for the demodulator-decoder coupler. As can be noted, the probability of survival for 30 days has been increased from 95.588% to 99.86%. This corresponds to a 31.5 to one reduction in system unreliability. The antenna coupler has been considered to contribute negligibly to system unreliability. It is of printed circuit construction and contains no active components and relies principally upon its geometry which is rigidly fixed for its performance.

As stated earlier, reliability improvement can be gained through redundancy utilizing the inoperative standby mode and activating the redundant unit only when required. Assuming initially a zero failure rate for the sensing and switching mechanisms the reliability model takes on the configuration shown in Figure 11 and the mathematical relation as follows:

P(t) redundant, standby, inoperative =

$$\left[P_{\text{Rcvr 1}}(t) + (\lambda_{\text{Rcvr 1}} \cdot t)(P_{\text{Rcvr 2}}(t))\right]$$

$$\left[P_{\text{Demod 1}}(t) + (\lambda_{\text{Demod 1}} \cdot t)(P_{\text{Demod 2}}(t))\right]$$

$$\left[P_{\text{Decoder 1}}(t) + (\lambda_{\text{Decoder 1}} \cdot t)(P_{\text{Decoder 2}})\right]$$

Utilizing the probability of survival for the various command control functions gives the following:

$$P(t)_{\substack{\text{Redundant} \\ \text{standby,} \\ \text{Inoperative}}} = \left[P(t)_{\text{Rcvr.}}\ (1+\lambda t)\right]$$

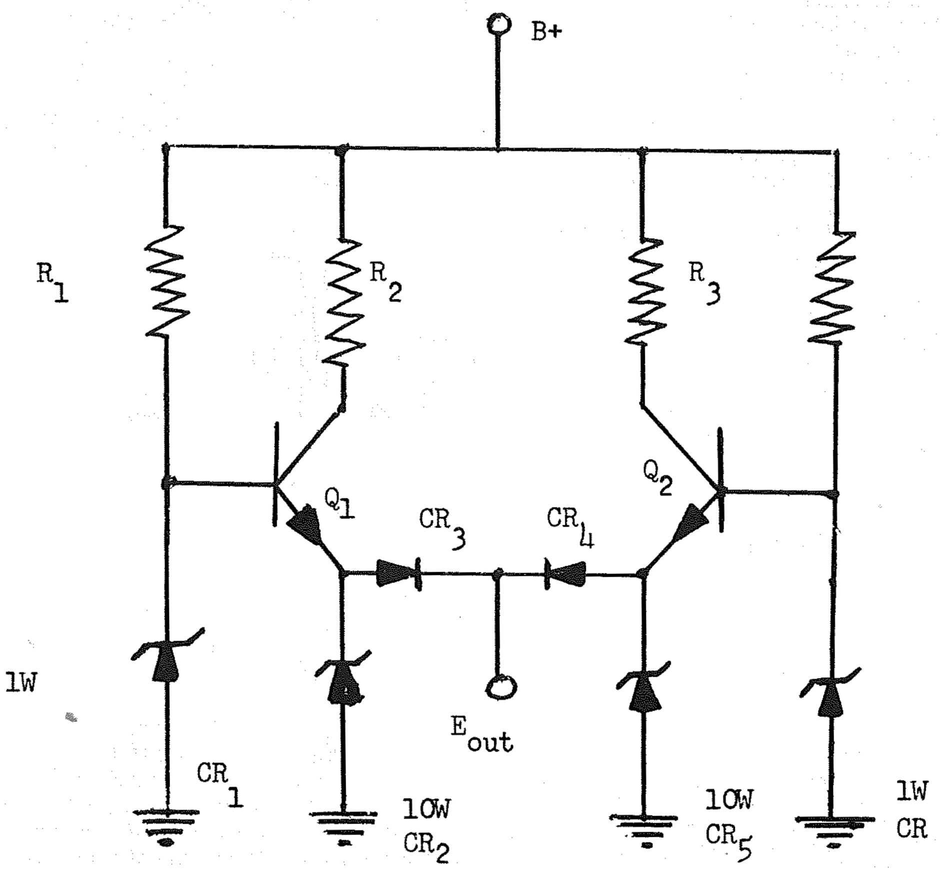
$$\left[P(t)_{\text{Demod.}}\ (1+\lambda t)\right] \left[P(t)_{\text{Decoder}}\ (1+\lambda t)\right] \text{ exists if:}$$

$$P(t)_{\substack{\text{Rcvr.} \\ \#1}} = P(t)_{\substack{\text{Rcvr.} \\ \#2}};\quad P(t)_{\substack{\text{Demod.} \\ \#1}} = P(t)_{\substack{\text{Demod.} \\ \#2}};$$

$$P(t)_{\substack{\text{Decoder} \\ \#1}} = P(t)_{\substack{\text{Decoder} \\ \#2}}$$

The reliability of P_t of the redundant standby inoperative command control exclusive of the sensing and switching is 99.999%. Allowing for the necessary sensing and switching reduces the probability of survival for this subsystem to a level substantially equal to that of the product of the probability of survival of the required sensing and switching elements. Since the receiver demodulator and decoder functions have a probability approaching unity over the interval of time (t), it is apparent from the 3 cases illustrated that the greatest net reliability gain can be achieved using the operate standby redundancy.

The outputs from the two decoders are fed to the command control box to performing command functions. The most critical circuits in the control box are the two voltage regulators which are common to each control channel. A failure in either of these circuits causes the complete loss of spacecraft control. Therefore complete parallel redundant regulators have been provided as illustrated in Figure 12. Review of the circuit illustrates that combina-



Redundant Regulator Control Box

tions of particular failure modes are necessary to cause the regulator voltage to exceed its useful range. It will be noted that the most critical failure mode in the regulator is the open circuit. Should a component part open in each regulator circuit this would cause the loss of the output voltage. However, the open failure is usually contributable to overload stress conditions that occur as the results of shorts occuring in other series elements or, in the case of the semi-conductor devices, a result of transient voltage conditions that exceed the mamimum ratings of the part. Both overload conditions such as this have been controlled by careful selection of component parts and their application.

Should Q_1 or Q_2 fail in a shorted condition collector to emitter the load resistors are capable of absorbing the additional voltage drop without overloading. The 10 watt zener will absorb the additional current loading and still remain within its zener voltage and power dissipation rating. Effective control of the voltage will be maintained under these conditions. Further analysis will indicate that it requires three components failures by short in a single circuit before the regulator will cause a system malfunction. The reliability numerics for the circuit are based however on the worse case condition of one component in each regulator will fail due to opens. The redundancy decreases the probability of failure from 3.5 chances in 1000 to 2.0 chances in 10,000.

Twenty command channels are provided by the control box which provides individual "on" switching to each redundant and single element in the system. The "off" commands, for both wideband repeaters and telemetry transmitters are coupled together, primarily due to lack of command signals. Loss of either of these circuitswould allow the associated equipments to remain in the "on" condition. This problem is not as severe as it first looks since the telemetry transmitters only draw 250 milliwatts each and the wideband repeaters which draw 75 watts each are provided with other cut-off means. This emergency cut-off is the low voltage sensing network, mentioned earlier in the power supply, which generates and feeds a negative pulse through the "on" control circuitry thus turning the series regulators to the "off" position.

In addition to this, loss of RF energy in the wideband receiver generates an additional turn "off" pulse to the series regulators. Loss of any of the other command circuits will, of course, remove the associated equipment from use but due to the redundancy, this will only reduce the systems effectiveness.

Telemetry Circuitry

The telemetry subsystem includes the experimental and telemetry data encoder, the horizon scanner and two telemetry transmitters. One of the transmitters will be utilized the majority of the time as a tracking beacon and the other will be utilized to transmit either the encoder or the horizon scanner data. This set of transmitters have been considered as a redundancy configuration since as long as one transmitter survives, the data and tracking function can be time shared. The time sharing programming can be accomplished from ground at the discretion of operating personnel. This does reduce the system's effectiveness but it does not cause complete abortion of the telemetry transmission.

Conclusions

The incorporation of redundancy within Project Relay improves the probability of mission success for the complete communication system to 0.9508. The wideband TV and telegraphy transmission subsystem to 0.9935 and the telemetry transmission subsystem to 0.9534. These values represent gains of 1.5, 11.7, and 2.76, respectively over that of the non-redundant counterpart. Table 1 is a tabulation of both the non-redundant and redundant areas to illustrate the reliability gain.

Table 1

Circuit	Non-Redundant	Redundant
System Power Supply	0.9814	0.9961
Solar Panels	0.9997	0.9997
Voltage Limiter	0.9972	0.9972
Battery Charge and Control Circuit	0.9854	0.9993
Series Diodes to Unregulated Bus	0.9991	0.9991
Command Circuitry	0.9525	0.9978
Command Receiver and Demod.	0.980	0.9996
Coupling Circuit		0.9994
Decoder	0.972	0.9992
Telemetry Circuitry	0.9375	0.9570
Encoder	0.9716	0.9716
Horizon Scanner & SCO	0.9874	0.9874
Modulator-Encoder Switching	0.9957	0.9957
Telemetry Transmitter	0.9806	0.9806
Wide-band Transponder	0.9912	0.9996
Regulator	0.9985	
On-Command	0.9998	
Receiver	0.995	
TV-Phone Switch	0.9999	
2 Minute Timer	0.9996	
Transmitter	0.9987	
TV-Phone Drive	0.9998	
Off-Command	0.9999	
Communications System	0.9266	0.95

'9a' f.x.

PREDICTING SPACE MISSION SUCCESS THROUGH TIME-STRESS ANALYSIS

I. Doshay and H.L. Shuken,

Space-General Corporation, El Monte, California

17282

Abstract

A technique of reliability prediction is introduced which encompasses the review of vehicle components, their periods of active and passive performance, and the schedule of operational stresses involved in the mission. This methodology is applied to Ablestar space program upper stage vehicles, where component reliabilities are established from prior experience using ground test criteria. This is interpreted as the unity stress level, upon which basis the reliability of the vehicle is constructed. It is accomplished by tracing each significant vehicle function and accompanying operational time-stress through the progress of the intended vehicle mission. After the vehicles are fabricated, comparisons are made of the prior published predictions and subsequent tests on the actual vehicles. The results are seen to be very encouraging for further application of this technique.

The flight proven propulsion reliability is found to correlate with predicted values within 1% differential. The newly developed electronic portions do not correlate as well, i.e. vary up to 10%. However, there are specific problems that point to reasons these items are not within state-of-the-art range of expectancy.

The details of the analysis of propulsion system and electronics portions of the vehicle are given. These include establishing failure rates, operational stresses and the resultant reliability calculations for two pre-defined levels of mission success. An appendix is provided disclosing the determination of confidence limits and the calculation of same. Twelve tables are included listing failure expectancies of propulsion and electronic components, duration of operational time stresses, functional breakdown of Ablestar stage, list of critical items and their failure rates, expected failure rates under non-firing tests and failure rates of components experienced in Ablestar systems produced subsequent to the pre-hardware prediction.

Defining the Objectives

An analysis was made of the reliability of the Ablestar stage based on the design parameters and available time-related failure data on propulsion and airborne electronics component parts prior to assembly of the first complete system in 1960.

Reliability was defined in accordance with AFBM Exhibit 58-10, Reliability Program for Ballistic Missile and Space Systems, which stated:

"Reliability - The probability that an item will operate within specified limits for the time and operating conditions specified, utilizing support equipment and procedures in the manner intended."

The "specified limits" referred to in the above definition of reliability are defined by the Model Specification or manufacturer's quoted specification limits. Use of supporting equipment and procedures implies that the vehicle will be in perfect functioning condition at the time of launch. Although performance outside specification limits is construed herein as failure (unreliable), it should be noted that specifications generally allow considerable safety margin. Therefore, flight abort will not necessarily be the result of operation outside of specified limits.

For the purposes of this analysis, the Ablestar stage is considered to be composed of two different major systems, the AJ10-104 propulsion system and the Ablestar Forward Section.* Since the coast times for the Transit 2-B and Courier 1-B are different, a separate reliability estimate was made for each. Also, it is of interest to find (1) the probability of all parts functioning in accordance with specifications, so that the flight may be called "perfect"; and (2) of finding the probability of all "essential" parts functioning in accordance with the specifications for the mission functions, so that the flight may be called acceptable. Table A shows the above mentioned reliabilities with 95% confidence limits. The calculation methodology and these estimates are described in detail below, and in the Appendix. Comparison of these predictions with reliability calculations from ground test duty on the first stage produced per Table B indicated the approach was valid for prediction on a single vehicle basis. Further substantiation was revealed as more vehicles were produced and launched (see Figure 1).

Basis of Analysis

Method of Analysis

The reliability predictions reflected in this analysis pertain to inherent design characteristics of the Ablestar vehicle. This does not include aspects of applications integrity hazards in the engineering, fabrication or field handling operations. It is anticipated that there is some probability such factors will degrade the inherent reliability; however, their effects are the considerations of the monitoring

*Exclusive of Advanced Guidance System

program desc[illegible]d in the latter part of the paper.

Inherent reliability calculations for this study are based on constant hazard time stress conditions. This follows from considerable experience with ballistic missiles and space vehicles, which has indicated that part failure may be equally likely to occur during any time in the vehicle flight while the parts are under stress.[1] With this constant hazard condition and the time stress periods of the operating components the low failure probabilities found are associated with the Poisson distribution of times to failure, T:

$$f(T) = \frac{M(t)}{T!} e^{-M}$$

where: M is mean time to failure

t is the operational time stress

For the non-failure condition we define the reliability model as:

$$R = e^{-t/M} = e^{-tf}$$

where f is the failure rate which is defined in the same time units as t.

Source of Failure Rates

The Failure Rates listed in the fourth column, "No. of Failures per 10^3 Hours in Manned Aircraft" of Table 1, "Failure Rates of Electronic and Associated Parts" are derived from Fire Control System equipment failure data during 10,000 system hours of flight operation. Failure rates on the propulsion system were obtained during static test firings and during propulsion system checkout tests. These failure rates are listed in Table 2. For the Unity Stress Level* during powered flight and coast, and for Ref. (1) Stress Level[2] during the coast period, this system is assumed to be under the same environmental stresses as a manned aircraft. Ground test data on system performance of the same components in other vehicles was used to estimate the failure rate of the Ablestar stage during first and second stage burning time. Component part failure rates for parts used in the Ablestar stage are shown in the discussion that follows below, and in Tables 4, 5, 6, and 7.

Reliability Levels and Stress Factors

The choice of the Unity Stress Level stems from the uncertainty in accepting stress level factors from reference sources. Since these factors were derived from systems which are not duplicated in the Ablestar configurations, it follows that these factors cannot be the same for both. To prescribe the complete range of possible reliability variation for the test data available, 95% confidence limits were determined. This is not be be confused with a confidence in the reliability of the vehicle, which could be established from actual flight successes.

Environment-Time Program

For each flight, the Ablestar stage may be described as experiencing five distinct environments from first stage "ride" to post burnout. These five environments are (1) the "ride" on the Thor, (2) the time of first firing of the "104" propulsion system, (3) the coast time, when the failure rate is assumed to be the same as for manned aircraft, (4) the period of re-start (second firing), and (5) the period beyond shutdown for the Spin Table actuation and the payload satellite separation. These times are shown in Table 3. The time between first stage burnout and second stage firing is not considered separately because it is too short in length to affect the overall calculations.

Analysis of the AJ10-104 Propulsion System

The AJ10-104 propulsion system reliability, when used in the Ablestar stage, was estimated on the basis of the best time-related failure data on this equipment available. The values are based on the accumulation of all recorded test data (time and replaced parts) from the Able program. As tests are continued on Ablestar vehicles the reliability and confidence reflected in this report were expected to become more valid or perhaps require readjustment. Since no prior methodology was available to predict rocket reliability in advance of actual hardware and tests on that hardware, much speculation was entertained on the accuracy of these predictions.

Estimation of Failure Rates

At the time of the analysis there were thirteen successful flights involving Able-type units prior to Ablestar or Delta. There also were four other Able units which, unfortunately, never had opportunity to perform due to malfunctions occurring in the first stage vehicles. The total flight time of these units was 1332 seconds, for an average of a little over 100 seconds operation per propulsion system. It was evident that a valid estimate could not be made with this data since the time on each unit was only a little more than 1/3 the expected AJ10-104 firing time and the total firing time was only four and one half times that of a single AJ10-104 propulsion system's operating time.

To obtain more operating time, data was obtained from the PFRT, Acceptance, and checkout tests of these prior vehicles flown. The "hot" firings for all vehicles added up to 3999 seconds. Based on ten checkout tests of AJ10-40 and AJ10-42 propulsion systems, the average checkout time of a single vehicle was found to be 64.4 hours. Therefore, it was concluded that the hot

*Hereinafter called USL.

firing test time was not sufficiently significant as added test time in this analysis. For seventeen vehicles the total checkout time was calculated as 17 x 64.4 = 1095 hours.

In determining the USL reliability this 1095 hours was used as the basis for determining the failure rates of propulsion system elements.

During the checkout and firing tests performed prior to the analyses there were 38 AJ10-104 applicable failures of one kind or another which could have happened in flight and would affect operation of the vehicle as specified. In addition to these there were other malfunctions which would not affect vehicle operations as specified and were therefore not included in this evaluation.

These 38 applicable failures were the basis of Table 8 which lists those failed items, and the number of these items on the propulsion systems, AJ10-40, 42, 101, and 104. The failure rate obtained is also listed in this table.

Environmental Conditions

The AJ10-104 reliability, however, is the product of several separate reliabilities because it has the restart capability and thus undergoes several environmental changes.

At lift-off the most severe vibration takes place as the first stage engine ignites. Combined vibration and acceleration environment continue for about 165 seconds before shutting off. During this time relatively few of the second stage parts are subjected to operating pressures. Those items which are subjected to pressures include the helium tanks, regulator valve, tubing, check valves, tank shut-off pilot valve, nitrogen tanks, regulator, lines, check valves, and hydraulic system. During this time no portion of the second stage propulsion system, including the attitude control sub-system, will be operating.

The first stage shutoff is followed by approximately two seconds of coast time before the second stage ignites.

The next operating phase takes place when the AJ10-104 ignites with combined acceleration, vibration, and high pressures and temperatures. This continues with all items being stressed until about 275 seconds have elapsed when the propulsion system shuts down for 20-30 minutes of coast depending on the mission. During this coast period the hydraulic pump shuts down; the coast attitude control (nitrogen system) functions while the propellant tank and almost all lines remain under pressure. The coast period is followed by a 15-20 second AJ10-104 firing in which all portions of the system are required to operate again. This is followed by the final low stress coast period when the spin-table spins up and ejects the payload. This coast period is about 17 seconds. At this point the Ablestar Stage has completed its mission.

Determination of Reliability

Reliability calculations were made for both the perfect and acceptable flight situations: as defined earlier.

Perfect Flight. The reliability of the AJ10-104 propulsion system, including the Gimbaling system, is computed as

$$R = \exp -\left[t_1 f_1 + t_2 f_2 + t_3 f_3 + t_4 f_4 + t_5 f_5\right]$$

where t_1 refers to time under a particular stress and f_1 the failure rate during that time, the subscripts 1-5 have the same meaning as in the foregoing where "1" refers to the "ride" on the Thor, "2" to the first burning, "3" to the coast period, "4" to re-start firing and "5" to the period beyond shutdown during the spin table actuation.

The following discussion shows the method of determining the reliability of the propulsion system for the Transit 2-B. The total failure rates of the subassemblies of the AJ10-104 propulsion system are shown in Table 4 and the failure rates of the individual elements are shown in Table 6. The total failure rate for all items is 55.76 failures per 1000 hours for the unity stress level.

During the "ride" on the Thor, the thrust chamber assembly and the TPS switch are not under stress so f_1 = 55.76 - 6.56 (Ground Test Failure Rate of TCA) -0.92 (Failure Rate of TPS Switch) = 48.28 failures per 1000 hours for the unity stress level. During the first burning of the AJ10-104, the failure rate f_2, is 55.76.

During the coast periodthe TCA, TPS switch, and Gimbaling components are not operationally stressed so f_3 = 55.76 - 6.56 (Ground Test Failure Rate of TCA) - 0.92 (Failure Rate of TPS switch) - 4.58 (Failure Rate of Gimbaling components including hydraulic accumulator) = 43.70 failures per 1000 hours for the unity stress level. During the restart firing the settling valve does not need to operate further so f_4 = 55.76 - 1.82 = 53.94 failures per 1000 hours for the USL level. During the 17 seconds coast period beyond shutdown, only the fuel tank pressure system needs to operate and this has a failure rate of 2.24 failures per 1000 hours for the USL.

Hence for the USL

$$R = \exp -\left[\frac{165\ (48.28)}{3600\ (1000)} + \frac{282\ (55.76)}{3600\ (1000)} + \frac{1260\ (43.70)}{3600\ (1000)} + \frac{12\ (53.94)}{3600\ (1000)} + \frac{17\ (2.24)}{3600\ (1000)}\right]$$

$$= e^{-.0221} = .978$$

Acceptable Flight. The following reliability estimate is based on the assumption that items such as propellant gas fill quick disconnects

and oxdizer vent valves are items which do not function or operate after initial loading. Any leak in these items will be detected while the vehicle is still on the ground. It is also noted that the pressure transducers are not essential for acceptable operation.

Table 4 shows that the total failure rate for all items is 55.76 failures per 1000 hours for the unity stress. The failure rates of parts which do not need to function for an acceptable flight must be subtracted from these figures.

The following tabulates the failure rates of these items not under consideration for an acceptable flight:

	USL F.R./1000 Hours
2 oxidizer Probes	1.84
9 Transducers	6.74
9 Quick Disconnects	1.64
1 Oxidizer Vent Valve	1.82
TOTAL	12.04

So the Failure Rate of all items under consideration is 55.76 - 12.04 = 43.72 failures per 1000 hours for the unity stress level.

Items not required to function or not stressed during first stage operation are:

		USL F.R./1000 Hours
Thrust Chamber	(1)	6.56
Thrust Chamber Prop Valves	(2)	5.48
TC Prop Valves Pilot Valves	(2)	2.74
Flex Lines (propellant)	(3)	2.74
Pressure Switches	(2)	1.82
Fuel Vent Valve		.90
Miscellaneous (lines, gaskets, "O" rings, sleeves, etc.		1.74
Total failure rate of items not required to operate during 1st stage operation		21.98

The total failure rate estimate of all essential and functional items in the AJ10-104 propulsion system is 43.72 failures/1000 hours for the unity stress level. Therefore, the failure rate, f_1, during the first stage ascent is 43.72 - 21.98 or 21.74 failures/1000 hours for the USL level.

During the first burning of the AJ10-104, the failure rate, f_2, is 43.72 failures per 1000 hours for the USL.

The items which are not required to function or are not under pressure through the coast period are:

	USL F.R./1000 Hours
Thrust Chamber	6.56
TPS Switch	.92
Gimbaling equipment/shutoff during coast time	3.66
Helium Regulator	1.82
Hydraulic Accumulator	.92
Total Failure Rate of Items not under Stress	13.88

Using the above listing it is seen that the failure rate, f_3, during coast period for the USL is 43.72 - 13.88 = 29.84 failures/1000 hours. During the restart firing the settling valve doesn't need to operate further so f_4 = 43.72 - 1.82 = 41.90 failures/1000 hours for the unity stress level. As in the case of perfect flight, f_5, the failure rate during the final 17 second coast period, is 2.24 failures/1000 hours for the USL.

Hence for an acceptable Transit 2-B flight, the USL is

$$R = \exp - \left[\frac{165\ (21.74)}{3600\ (1000)} + \frac{282\ (43.72)}{3600\ (1000)} + \frac{1260\ (29.84)}{3600\ (1000)} + \frac{12\ (41.90)}{3600\ (1000)} + \frac{17\ (2.24)}{3600\ (1000)} \right] = e^{-.0150} = .985$$

Calculations for Courier 1-B. The calculation for the Courier mission was made in a similar manner as for the Transit 2-B flight. For the Courier 1-B system the Failure Rates for all environments are the same as for the Transit 2-B. The only difference in reliability of the propulsion system is due to the longer coast time. The USL of a "perfect" Courier 1-B AJ10-104 propulsion system is

$$R = \exp - \left[\frac{165\ (48.28)}{3600\ (1000)} + \frac{282\ (55.76)}{3600\ (1000)} + \frac{2100\ (43.70)}{3600\ (1000)} + \frac{12\ (53.94)}{3600\ (1000)} + \frac{17\ (2.24)}{3600\ (1000)} \right] = e^{-.0323} = .968$$

the USL level of an "acceptable" Courier 1-B AJ10-104 propulsion system is,

$$R = \exp - \left[\frac{165\ (21.74)}{3600\ (1000)} + \frac{282\ (43.72)}{3600\ (1000)} + \frac{2100\ (29.84)}{3600\ (1000)} + \frac{12\ (41.90)}{3600\ (1000)} + \frac{17\ (2.24)}{3600\ (1000)} \right] = e^{-.0220} = .978$$

A similar calculation was performed to obtain the Transit 3-A reliability prediction.

Analysis of the Ablestar Stage Forward Section

The reliability of the Forward Section of the Ablestar Stage was estimated from relatively recent failure rates of electronic components found in 10,000 system hours of flight operation of Fire Control System equipment. The total failure rate as shown in Tables 5 and 7 is 12.62 failures per 1000 hours for the USL level for "perfect" flight of the Transit 2-B (i.e., when all components are operating in accordance with specifications); this is the failure rate during the whole flight except for the 17 seconds of spin table actuation after restart burnout. On the Courier 1-B the Assembly Integrating Accelerometer needn't function after the first burnout so the failure rate becomes 12.62 - 1.08 = 11.54 failures per 1000 hours for the USL during the coast and restart periods. The failure rate of the components in the Forward Section directly connected to and including the spin table is .38 failures per 1000 hours for the USL. These reliability calculations do not include the STL guidance package which was Government-furnished and thus treated as external to the Ablestar Stage as supplied by Aerojet-General Corporation. In the case of "acceptable" flight where only operation of essential parts is considered, the failure rate for the telemetry system may be neglected and the overall failure rate for the Transit 2-B becomes 12.62 - 3.08 = 9.54 failures per 1000 hours for the USL. For "acceptable" Courier 1-B the failure rate is 11.54 - 3.08 = 8.46 failures per 1000 hours for the USL during the coast and restart periods.

The following calculations show the USL reliability estimates of the Forward Section Assembly.

For a "perfect" flight the forward section estimated USL reliability for the Transit 2-B is,

$$R = \exp - \left[\frac{165\ (12.62)}{3600\ (1000)} + \frac{282\ (12.62)}{3600\ (1000)} + \frac{1260\ (12.62)}{3600\ (1000)} + \frac{12\ (12.62)}{3600\ (1000)} + \frac{17\ (0.38)}{3600\ (1000)} \right] = e^{-.006} = .994$$

For an "acceptable" flight the forward section estimated USL reliability for the Transit 2-B is,

$$R = \exp - \left[\frac{165\ (9.54)}{3600\ (1000)} + \frac{282\ (9.54)}{3600\ (1000)} + \frac{1260\ (9.54)}{3600\ (1000)} + \frac{12\ (9.54)}{3600\ (1000)} + \frac{17\ (0.38)}{3600\ (1000)} \right] = e^{-.005} = .995$$

For a "perfect" flight the forward section estimated USL reliability for the Courier 1-B is,

$$R = \exp - \left[\frac{165\ (12.62)}{3600\ (1000)} + \frac{282\ (12.62)}{3600\ (1000)} + \frac{2100\ (11.54)}{3600\ (1000)} + \frac{12\ (11.54)}{3600\ (1000)} + \frac{17\ (0.38)}{3600\ (1000)} \right] = e^{-.008} = .992$$

For an "acceptable" flight the forward section estimated USL for the Courier 1-B is,

$$R = \exp - \left[\frac{165\ (9.54)}{3600\ (1000)} + \frac{282\ (9.54)}{3600\ (1000)} + \frac{2100\ (8.46)}{3600\ (1000)} + \frac{12\ (8.46)}{3600\ (1000)} + \frac{17\ (0.38)}{3600\ (1000)} \right] = e^{-.006} = .994$$

Reliability Monitoring

In order to assure that the reliability predicted in this report was obtained, it was necessary to monitor the components as they were tested. The maximum number as well as the average number of failures for each component are given in Tables 9 and 10. For example, from reading Table 9 we infer that if all the black boxes containing capacitors were tested for 1000 hours each we would not expect any failures. Even if there were as many as three failures of capacitors, this may still be acceptable as random expectancy; however, four failures would indicate the failure rate was excessive. In the event four or more failures were experienced, an investigation as to the nature of the failures would be made. Similarly, the maximum number of coils, connectors, diodes, and other electronic parts which may fail in ground test due to chance causes can be read from Table 9. If, for instance, the total test time per black box were 100 hours, we could not allow any failures except for one each in diodes and resistors without initiation of suitable corrective action. Table 10 lists the propulsion system items and their maximum failure rates, and is interpreted in the same manner as Table 9.

Initial Results of Monitoring

From the first two vehicles produced, data was derived from ground tests performed on these vehicles that reflected amazingly close correlation of failure rates (and hence reliabilities) with the anticipated figures for the propulsion subsystem. The results of electronics tests indicated several units were not within expected failure rate limitations as previously described. A tabulation of these initial findings is shown in Table 11 with reliability interpretation shown in Table 12. Changes were initiated in the electronics portions of the stage early in the program to remove obvious items of equivocal performance. As these changes were incorporated the reliability of electronics showed distinct improvement. Examples of a monitoring chart and of monitoring graphs are shown in Table 13 and Figure 2 respectively. A new analysis of the entire Ablestar Stage in its current configuration is now in process using actual Ablestar failure data and flight stress factors including environment. In 7 flights in which the Ablestar Stage has been called upon to perform to data 6 have been acceptable, that is 86 percent.

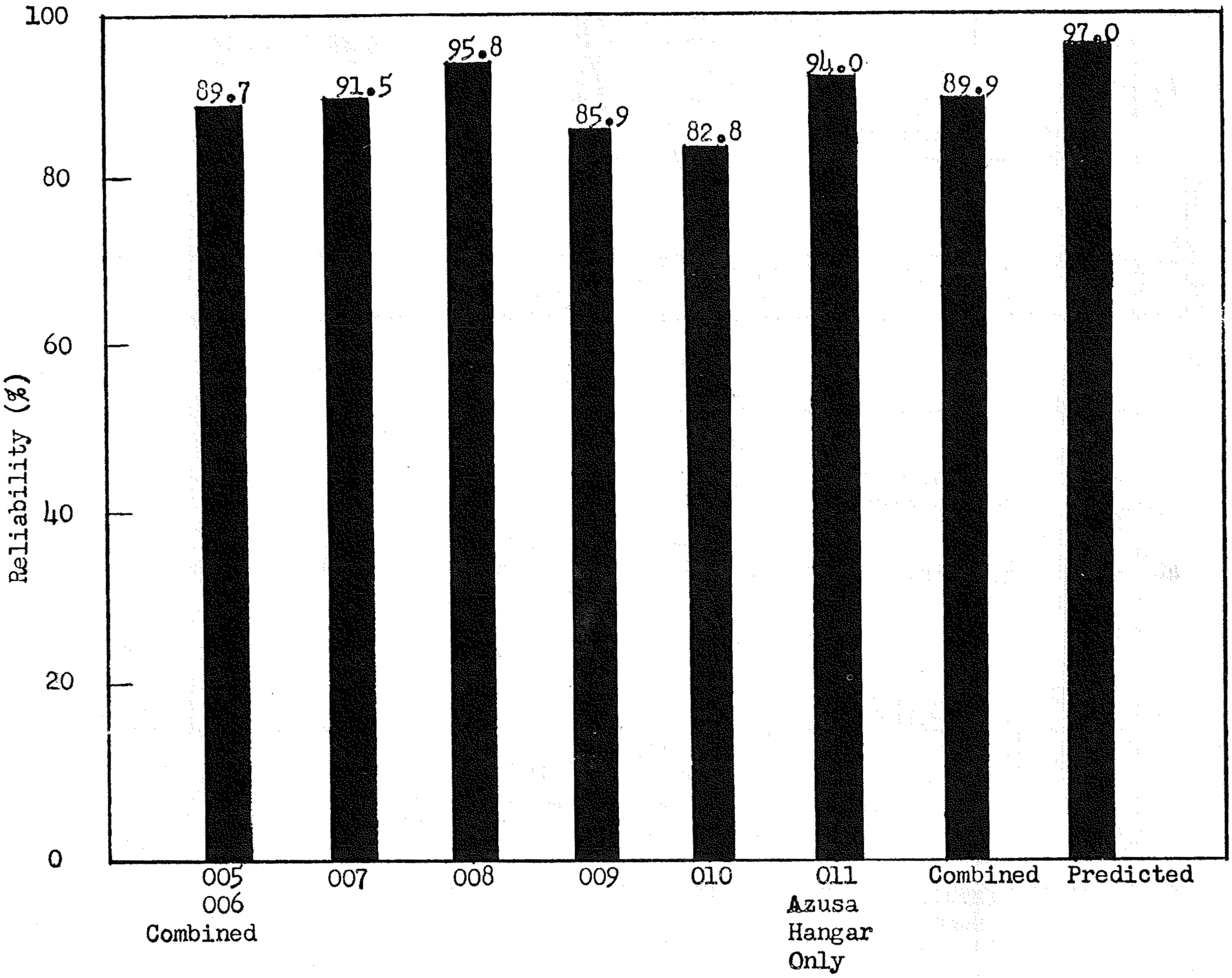
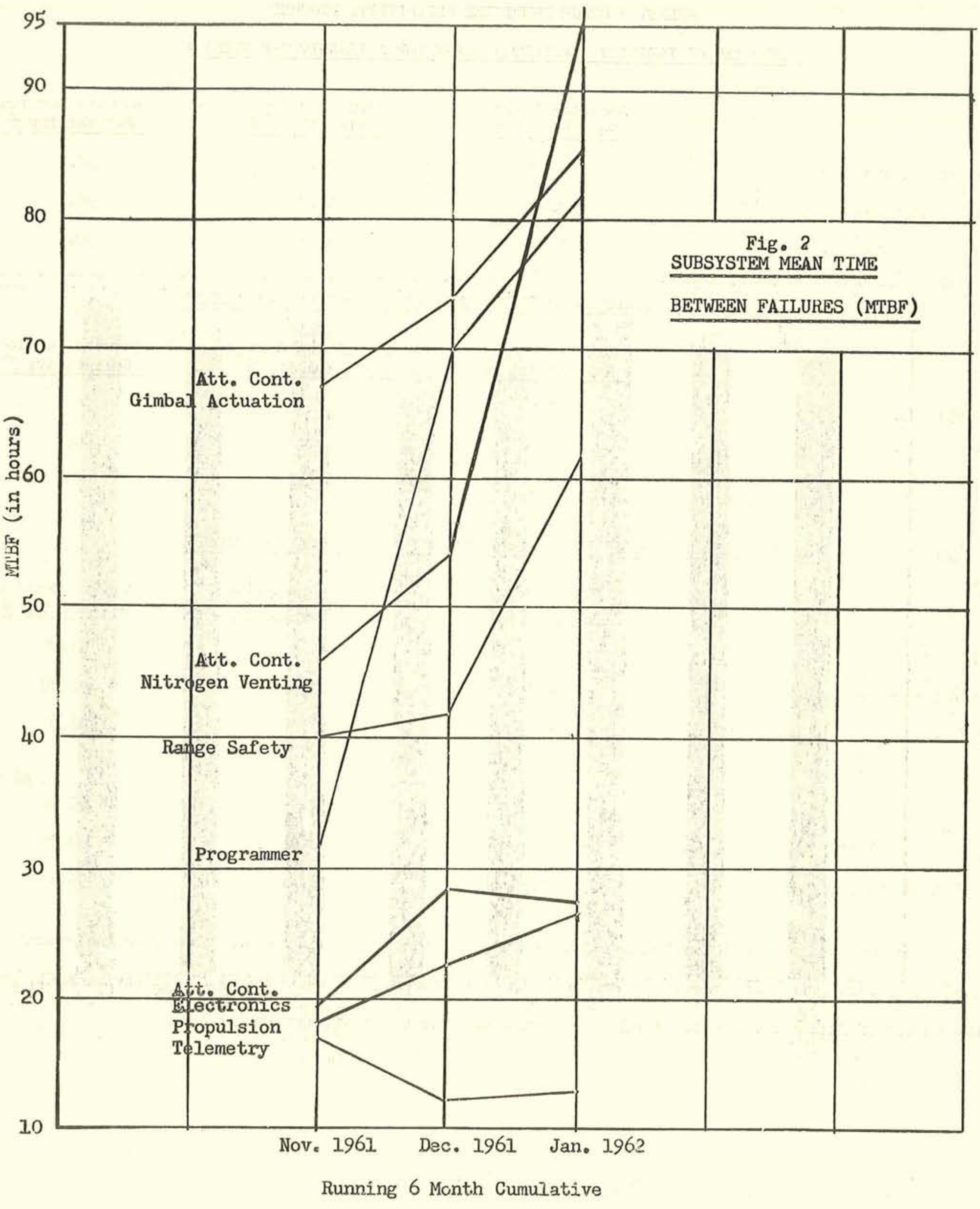


Figure 1

Reliability of Ablestar Stages



Note: The Electrical Power Subsystem is not shown on this graph. With only one failure, occuring in January, we have a subsystem MTBF of 204.1 hours for January 1962.

TABLE A

ABLESTAR STAGE PREDICTED RELIABILITY FIGURES

PREDICTED RELIABILITY - ABLESTAR STAGE FOR A TRANSIT 2-B MISSION

	Ablestar Stage Reliability %	Propulsion System Reliability %	Forward Section Reliability %
Perfect Flight	97.2	97.8	99.4
95% Lower Confid. Level**	96.5	96.8	99.4
95% Upper Confid. Level**	97.9	98.3	99.4

PREDICTED RELIABILITY - ABLESTAR STAGE FOR A COURIER 1-B MISSION

	Ablestar Stage Reliability %	Propulsion System Reliability %	Forward Section Reliability %
Perfect Flight	96.0	96.8	99.2
95% Lower Confid. Level	95.0	95.4	99.1
95% Upper Confid. Level	97.0	97.6	99.2

PREDICTED RELIABILITY - ABLESTAR STAGE FOR A TRANSIT 3-A MISSION

	Ablestar Stage Reliability %	Propulsion System Reliability %	Forward Section Reliability %
Perfect Flight	96.1	97.2	98.85
95% Lower Confid. Level	95.4	95.92	98.78
95% Upper Confid. Level	96.7	97.87	98.94
Acceptable Flight	96.98	97.9	99.06
95% Lower Confid. Level	96.53	96.95	98.99
95% Upper Confid. Level	97.35	98.41	99.13

** The upper and lower 95% confidence level pertains to the reliability value found when the ground test and coast environment is assumed to be of the same severity as the powered flight environment, and the number of failures reflected during the source data test periods are considered.

TABLE B

ABLESTAR STAGE RELIABILITY FIGURES FROM GROUND TESTS

OF S/N 005 AND 006, AZUSA AND CAPE CANAVERAL

CURRENT RELIABILITY - ABLESTAR STAGE S/N-005 (COURIER 1-B MISSION)

	Ablestar Stage Reliability %	Current F/Hr.	Propulsion Syst.Rel.%	Current F/Hr.	Fwd. Sec. Rel.-%
Perfect Flight	85.15	.0635	95.97 *1	.16581	88.73
95% Lower Confid. Level	80.42		*2		83.60
95% Upper Confid. Level	88.74		*2		91.58

CURRENT RELIABILITY - ABLESTAR STAGE S/N-006 (TRANSIT 3-A MISSION)

	Ablestar Stage Reliability %	Current F/Hr.	Propulsion Syst.Rel.%	Current F/Hr.	Fwd. Sec. Rel.-%
Perfect Flight	86.06	.0635	96.45 *1	.16581	89.23
95% Lower Confid. Level	81.40		*2		84.45
95% Upper Confid. Level	89.33		*2		92.03
Acceptable Flight	90.38		96.45 *1		93.70
95% Lower Confid. Level	84.65		*2		89.08
95% Upper Confid. Level	92.86		*2		95.60

*1 - Includes Attitude Control System as per Report No. L 0358-01-10, Section III

*2 - Insufficient Number of Failures to Establish Confidence Limits

TABLE 1

FAILURE RATE OF FORWARD SECTION (ELECTRONIC) PARTS
BASED ON PRIMARY FAILURES

Part Type	Component Test-Hours	Failures	No. of Failures per 10^3 Hours in Manned Aircraft*
Capacitors	27.33×10^6	31	.00113
Coils, Chokes, Reactors, Mag. Amps, Filters	5.56×10^6	66	.01890
Crystals Semi-Cond. Diodes	57.50×10^6	84	.00146
Motors, Resolvers, Gyros, Synchros	$.42 \times 10^6$	33	.07857
Relays	4.31×10^6	158	.03673
Resistors	83.71×10^6	228	.00273
Switches	2.11×10^6	27	.01280
Transistors	1.29×10^6	35	.02713
Transformers	3.16×10^6	48	.01522
Total Failures		710	

* Derived from FCS equipment during 10^4 system hours flight operation

TABLE 2

FAILURE RATE OF PROPULSION SYSTEM (MECHANICAL)
BASED ON FAILURES IN VARIOUS GROUND TESTS

Part Type	USL Test Time Hours	Ref(1)Level Equiv. Test Time Hours	Failures	No. of Failures 10^3 Hours
Accumulator, Hyd.	1095	21.9	1	.914
Gimbal Equipment	1095	21.9	4	3.66
Harness, Connector	24090	481.8	4	.166
Line, Flex (propellant)	3218	65.6	3	.914
Line, High Pressure	251550	5031	4	.016
Oxidizer Probe	2190	43.8	2	.914
Pressure Switch	2190	43.8	2	.914
Quick Disconnect	5475	109.5	1	.183
Valve, Attitude Control(1)*				.914
Check	5475	109.5	1	.183
Fuel Vent(1)	1095	21.9	1	.914
Helium Vent(1)	1095	21.9	1	.914
Oxidizer Vent(1)	1095	21.9	2	1.828
Hydraulic Pressure				
Relief	1095	21.9	1	.914
Pilot	2190	43.8	3	1.372
Regulator	1095	21.9	2	1.828
FTCV	1095	21.9	5	4.572
OTCV	1095	21.9	1	.914
Total Failures			38	

(1) Valves with superscript (1) are all similar and are assumed to have the same failure rate.

* The time of testing attitude control was too small to consider.

TABLE 3

DURATION OF EACH ENVIRONMENT UNDERGONE BY ABLESTAR

Environment	Time (Seconds) Transit 2-B	Courier 1-B
Booster Duration	165	165
First Firing Duration	282	282
Coasting Duration	1260	2100
Second Firing Duration	12	12
Post Second Firing	17	17
Total	1736	2576

TABLE 4

FAILURE RATE OF AJ10-104 PROPULSION SYSTEM

Part	USL Expected Failures/1000 Hours	USL MTBF
Hydraulic System Installation, Gimbal Actuation	3.159	316.5
Line Valve Assemblies	6.208	161.1
AJ10-104 Main Assembly, Tanks	.397	2519
Transducer Installation	6.734	148.5
Thrust Chamber & Support Assy.	1.838	54.5
Harness Installation	.144	6945
Attitude Installation Control and Restart System	3.972	252
Attitude Control & Restart System Panel Assembly	7.757	129
Oxidizer Valve Hydraulic Assembly	1.205	830
Pneumatic System Installation Assembly	8.583	116.5
Thrust Chamber Assembly	12.469	80.0
Fill & Drain System Installation	3.223	310.5
Oxidizer Tank Pressurization Installation	.039	25640
Safety and Arming Destructor	.015	65800
Tank Assembly	.024	41665
Overall Failure Rate	55.76	17.93

TABLE 5

FAILURE RATE OF ABLESTAR FORWARD SECTION ASSEMBLY

Part	Burnout Test Failures/1000 Hours	USL MTBF
Spin Table	.379	2,638
Gyro Reference Assembly	.520	1,922
Battery & Control Box Assy.	.114	8,740
Telemetry Battery Assembly	.036*	27,780
Battery Assembly	.002	500,000
DC-DC Converter Assembly	.145*	6,880
Telemeter Signal Conditioner	2.011*	497
Telemeter RF Assembly	.890*	1,123
Assembly Integrating Accelerometer	1.066	936
Electronic Assembly, FLT Control	4.380	228
Final Assembly Programmer and Sequence Control	2.623	381
Telemetry Antenna Assembly	.005*	185,200
Distribution Box	.427	2,340
Fairing Separation	.028	3,572
Overall Failure Rate	12.62	79.24
	3.08*	324.68
	9.54**	104.82**

* These items not essential for "acceptable" flight.

** Overall failure rate for essential items of "acceptable" flight.

TABLE 6

FUNCTIONAL PARTS IN THE AJ10-104 PROPULSION SYSTEM

Component Part	No. in System	Expected Ground Test Failures/ 1000 Hours
Accumulators	1	.144
Actuator Cylinder	2	.102
Capacitor	12	.004
Coil	1	.019
Connector, Electrical	33	.001
Connector, Mechanical	1	.002
Diode	7	.010
Fairing Assembly	5	.010
Fittings, Flanges, Elbows	112	.002-.006
Filters, mechanical	5	.002
Filters, Electrical	2	.005
Flex Lines, Propellant	3	.914
Manifold	3	.058
"O" Rings and Gasket	143	.001
Potentiometers	2	.027
Probe, Oxidizer	2	.005
Pump, Hydraulic	1	.270
Resistors	8	.022
Sleeves	183	.004
Switch, Pressure	2	.914
Tank Assembly, Propellant	1	.020
Tank Assembly, Helium	3	.002
Tank Assembly, Nitrogen	6	.001
Thrust Chamber Assembly	1	6.56
Tranducers	9	.070
Transformers	1	.001
Transistors	2	.054
Tubes	121	.016
Valves	45	1.83-4.572
Total Functional Parts	717	
Total Failure Rate		55.76 failures /1000 hrs.

TABLE 7

FUNCTIONAL PARTS IN THE FORWARD ASSEMBLY
(Failure rates are based on manned aircraft environment)

Component Part	No. in System	Expected test Failures/1000 Hours
Accelerometer	1	.079
Actuator, Explosive	4	.007
Actuator, Rollerlerf	1	.006
Amplifier, Bendix	1	.170
Amplifiers, Bulova and Composite	2	.178
Battery	33	.002
Bolt, Explosive	5	.002
Capacitor	89	.001
Chopper	1	.050
Coaxial Connector	1	.017
Coil Inductor	25	.019
Connector, Receptacle	50	.005
DC-DC Converter	1	.016
Diode	300	.001
Gyro Assembly	3	.008
Hardware Items	4	---
Heater Blanket	3	.004
Insulator	15	---
"O" Ring	4	.003
Pin	1	.005
Potentiometer	9	.027
Preamplifier	2	.140

TABLE 7 (Cont)

FUNCTIONAL PARTS IN THE FORWARD ASSEMBLY
(Failure rates are based on manned aircraft environment)

Component Part	No. in System	Expected test Failures/1000 Hours
Relay	29	.037
Resistor	634	.003
Shaft	1	.031
Spin Table	1	.006
Spring	18	.009
Switch	11	.013
Tachometer Motor	1	.078
Terminal	294	.001
Transducer	1	.150
Transformer	20	.015
Transmitter, Bendix	1	.534
Transistor, Sensistor	164	.027
Valve, Explosive	4	.013
Valve, Circle Seal	2	.130
VCO	10	.054
Total Functional Components	1746	

TABLE 8

FAILURE RATE DETERMINATION FOR CRITICAL ITEMS
BASED ON 1090 HOURS ACTUAL TEST TIME

Item	AJ10-40, 42, 101 Propulsion Systems			AJ10-104 Propulsion System	
	Critical Failures Recorded During Tests	Comp. in Propulsion System	USL Failure/ 1000 Hr.	Comparable Items in System	Expected USL Failure/ 1000 Hr.
Check Valve	1	5	.182	9	1.64
Gas Reg. Valve	2	1	1.828	2	3.66
FTCV	5	1	4.572	1	4.57
Gimbal Equipment	4	1	3.660	1	3.66
OTCV	1	1	.914	1	.91
Propellant Flex Lines	3	3	.914	3	2.74
Oxidizer Vent Valve	2	1	1.828	1	1.83
Fuel Vent Valve	1	1	.914	1	.91
High Pressure Liner (Tubes)	4	229	.016	298	4.66
Harness Connector	4	22	.163	33	5.37
Pilot Valves	3	2	1.376	3	4.12
Helium Vent Valves	1	1	.914	0	- -
Hydraulic Pressure Relief Valve	1	1	.914	1	.91
Hydraulic Accum.	1	1	.914	1	.91
Oxidizer Probe	2	2	.914	2	1.83
Pressure Switch	2	2	.914	2	1.83
Attitude Control Valve	0	2	.914	9	8.23
Quick Disconnects	1	5	.183	11	3.21
Helium Shutoff Valve	0	0	.914	1	.91
OTSV and FTSV	0	0	1.372	2	2.74
	38	281		382	55.00

TABLE 9

EXPECTED FAILURE RATES OF ELECTRONIC COMPONENTS
IN THE ABLESTAR STAGE UNDER NON-FIRING TEST CONDITIONS

Component Part	Number Used	Median F/R Per Hour	Max. F/R Per Hour	Total Median F/R Per Hour	Total Maximum F/R Per Hour
Accelerometer	1	7.86 x 10^{-5}	18 x 10^{-5}	7.86 x 10^{-5}	18 x 10^{-5}
Capacitor	89	0.113	4	10.1	356
Coil	25	1.89	7.5	47.2	188
Connector	50	.542	5	27.1	250
Diode	300	.146	4	43.8	1200
Gyros	3	7.86	18	23.6	54
Motor	1	7.86	18	7.86	18
Relay	29	3.67	5.5	106.4	159.5
Resistor	634	.273	2.5	173.1	1585
Switch	11	1.28	4	14.1	44
Terminal	294	.096	1.5	28.2	441
Transformer	20	1.52	7	30.4	1.40
Transistor	164	2.71	8	444.4	1312
Amplifiers	3	17.78	35.3	53.3	107
Pre-Amplifiers	2	13.98	27.9	28.0	56
Transmitter	1	33.36	107	53.4	107
VCO	10	5.38 x 10^{-5}	10.7 x 10^{-5}	53.8	107
Miscellaneous	109			110 x 10^{-5}	220 x 10^{-5}

TABLE 10

EXPECTED FAILURE RATE OF PROPULSION SYSTEM COMPONENTS
UNDER NON-FIRING TEST CONDITIONS

Component	No. in System	Failure Rate/Hr	Max. Failure Rate/Hr	Total Failure/Hour	Total Maximum Failure/Hour
Accumulator	1	14.2×10^{-5}	28.4×10^{-5}	14.2×10^{-5}	28.4×10^{-5}
Actuator Cylinder	2	10.2	20.4	20.4	40.8
Capacitor	12	.113	4.0	1.56	48.0
Coil	1	1.89	7.5	1.89	1.5
Connector, Electrical	30	.542	5.0	16.26	150.0
Connector, Mechanical	1	0.2	0.4	0.2	0.4
Diode	7	.146	4.0	1.02	28.0
Fairing Assembly	5	1.0	2.0	5.0	10.0
Fittings, Flanges	112	0.2-0.6	0.4-1.2	22.4-67.2	44.8-134.4
Filter, Mechanical	5	0.2	0.4	1.0	2.0
Filter, Electrical	2	2.0	8.0	4	16.0
Harness	3	9.14	18.28	27.4	54.8
Manifold	3	0.58	1.16	1.74	3.48
"O" Rings Gaskets	143	0.1	0.2	14.3	28.6
Potentiometer	2	2.72	5.44	5.44	10.9
Probe Oxidizer	2	0.52	1.04	1.04	2.08
Pump, Hydraulic	1	27.0	54.0	27.0	54.0
Resistors	8	.27	2.5	2.16	20.0
Sleeves	183	0.4	0.8	73.2	146.0
Switch, Pressure	2	91.4	182.8	182.8	366.0
Tank Assembly, Propellant	1	2.0	4.0	2.0	4.0
Tank Assembly, Helium	3	0.16	0.32	0.48	0.96
Tank Assembly, Nitrogen	6	0.14	0.28	0.84	1.68
Thrust Chamber Assembly	1	656.0	1312.0	656.0	1312.0
Transducers	9	70.0	140.0	630.0	1260.0
Transformers	1	1.52	7.0	1.52	7.0
Transistors	2	2.7	8.0	5.4	16.0
Tubes, (lines)	121	1.64×10^{-5}	3.28×10^{-5}	198×10^{-5}	397×10^{-5}

TABLE 11

FORWARD SECTION (ELECTRICAL, SPIN TABLE & NOSE FAIRING)

	No. Failures	Time, Hrs.	Current Failure Rate F/Hr.
Range Safety	5	73.25	.06826
Electrical Power	1	292.07	.003423
Programmer	0	200.83	
Telemetry	19	271.77	.06991
Airborne Guidance	0	27.58	
Structural (Spin Table-Nose Fairing)	0	78.6	
Autopilot System,	6	330.28	.02422
Integrating Accelerometer	2		
			.16581

AJ-10-104 PROPULSION SUBSYSTEM + GIMBAL ACTUATION

& HYD. SUPPLY SYSTEM, AND NITROGEN GAS JET CONTROL SYSTEM

	No. Failures	Time, Hrs.	Current Failure Rate F/Hr.
Propulsion Subsystem	7	144.52	.04843
Gimbal Actuation Syst. & Hyd. Supply	4	330.28	.0151
Nitr. Gas Jet Control Syst.	1		
TOTAL F.R.			.0635

TABLE 12

SUMMARY, ABLESTAR STAGE FAILURE RATE & RELIABILITY

ABLESTAR STAGE S/N 005 & 006, AZUSA & CAPE CANAVERAL

Subsystem	No. Failures	Time Hrs.	Current Failure Rate, F/Hr.	Current Subsystem Reliabilities S/N-005	S/N-006
Range Safety	5	73.25	.06825	.9524	.9549
Attitude Control	13	330.28	.03936	.9791	.9801
Electrical Power	1	292.07	.00342	.9976	.9977
Propulsion	7	144.52	.04843	.9662	.9680
Programmer	0	200.83	0		
Telemetry	19	271.77	.06991	.9512	.9536
Airborne Guidance	0	27.58	0		
Structural	0	78.6	0		

* C Denotes Critical
M Denotes Major
m Denotes minor

Month Ending January 31, 1962

TABLE 13

SUBSYSTEM FAILURE DATA SUMMARY

Subsystem	Current Month					Six Month Cumulative					Predicted Failure Rate
	Failures*			Hours	Failure Rate **	Failures*			Hours	Failure Rate **	
	C	M	m	Hrs.:Min.		C	M	m	Hrs.:Min.		
Telemetry		2		39:18	.05089 ↓		12	1	182:00	.07142 ↓	.0014
Range Safety		1		21:48	.04587 ↑		1		62:18	.01605 ↓	.0021
Programmer				35:12	.0000 →		1	1	164:00	.01219 ↓	.0012
Electric Power	1			40:30	.02469 ↑	1			204:42	.00488 ↑	.0005
Control		2		36:42	.05449 ↑	2	5		194:30	.03598 ↑	.0069
Gimbal Act				13:30	.0000 →		1		85:48	.01165 ↓	.0047
N_2 Vent				8:30	.0000 →		1		95:18	.01049 ↓	.0073
Propulsion				4:00	.0000 →		5		128:12	.03900 ↑	.0341

This Subsystem Summary page is published in each Monthly Progress Report listing the failure rates, failures and hours for each subsystem for the current month and also a running six month's cumulative.

** Arrow- Indicates change from last month's report; down, up, or no change.

APPENDIX

CALCULATION OF CONFIDENCE LIMITS FOR RELIABILITY OF ABLESTAR STAGE

In general the 95% confidence limits of a reliability are computed as follows:

Compute the mean time between failures, M, and find the Reliability $R = e^{-t/m}$; then taking N as the number of failures used in computing M, find lower MTBF as $L = M - 1.96\, M/\sqrt{N}$ and upper MTBF as $U = M + 1.96\, M/\sqrt{N}$. As the failure rates in the different environments are different, it is necessary to find an equivalent time, T, and equivalent MTBF, M; so, the equations used in major Paragraphs 3 and 4 of the section can be transformed from

$$R = \exp - \frac{t_1}{M_1} - \frac{t_2}{M_2} - \frac{t_3}{M_3} - \cdots - \frac{t_5}{M_5} \quad \text{to} \quad R = e^{-T/M}$$

Table A-1 tabulates M and T for the various unity stress level cases. The values of T/M are shown in the body of the paper.

From Table 1 it is seen that 710 failures occurred during the testing for evaluating the Failure Rate of the most numerous components in the forward section, and from Table 2 it is seen that 38 failures occurred during the testing of propulsion systems. So, for the forward section, n is considered to be 710 with $\sqrt{n} = 26.65$; and for the AJ10-104 propulsion system, n is 38 with $\sqrt{n} = 6.16$.

Table A-2 shows T and M as well as confidence limits for the unity stress level.

The technique of "Tolerancing by the Differential Method"[3] was used in finding the confidence limits for the overall system (i.e., propulsion system and forward section).

In this method if $F = F(x,y)$ and the standard deviations s_x and s_y are known or are estimated, then the standard deviation of F can be computed as

$$SF = (F_x{}^2\, s_x{}^2 + F_y{}^2\, s_y{}^2)^{1/2}$$

In the present case $F = R_1 R_2$ where R_1 is the reliability of the propulsion system and R_2 is the reliability of the forward section.

Now $F_{R_1} = R_2$ and $F_{R_2} = R_1$. In computing the upper limit, $S_{RU_1} = (R_{U_1} - R_1)\, 1/1.96$ and $S_{RU_2} = (R_{U_2} - R_2)\, 1/1.96$ where R_{U_1} and R_{U_2} are upper limits for the reliabilities of the propulsion system and forward sections respectively. Similarly $S_{RL_1} = (R_1 - R_{L_1})\, 1/1.96$ and $S_{RL_2} = (R_2 - R_{L_2})\, 1/1.96$ are computed where R_{L_1} and R_{L_2} are the lower limits for the reliabilities.

The upper 95% limit of reliability is,

$$R_1 R_2 + 1.96 \cdot \sqrt{R_2{}^2 (R_{U_1} - R_1)^2 \left(\frac{1}{1.96}\right)^2 + R_1{}^2 (R_{U_2} - R_2)^2 \left(\frac{1}{1.96}\right)^2}$$

$$= R_1 R_2 + \sqrt{R_2{}^2 (R_{U_1} - R_1)^2 + R_1{}^2 (R_{U_2} - R_2)^2}$$

and the lower 95% limit of reliability is,

$$R_1 R_2 - \sqrt{R_2{}^2\, (R_1 - R_{L_1})^2 + R_1{}^2\, (R_2 - R_{L_2})^2}$$

References

1. Maj.Gen. L.J. Davis, Reliability in Missile and Space Operations IRE Transactions, February 8, 1961.
2. Reference (1) MMP 59-21 Published by Martin Co., Denver, Colorado, 9 July 1959.
3. Tolerancing by the Statistical or Differential Method, by Dr. J.N. Berrettone, Page 98, Automotive Supplement No. 1, published by American Society for Quality Control, May 1954.

TABLE A-2

95 PERCENT CONFIDENCE CALCULATIONS FOR SUB-SYSTEMS

Type of Analysis	M Sec.	T Sec.	$\frac{1.96\ M}{\sqrt{n}}$	95% Confidence Limits on MTBF Lower	95% Confidence Limits on MTBF Upper	95% Confidence Limits on Reliability Lower	95% Confidence Limits on Reliability Upper
Transit 2-B perfect propulsion system	78,500	1736	25,000	53,500	103,500	96.8	98.3
Transit 2-B acceptable propulsion system	116,000	1736	37,000	79,000	152,500	97.8	98.7
Courier 1-B perfect propulsion system	80,000	2576	25,000	54,000	105,000	95.4	97.6
Courier 1-B acceptable propulsion system	117,000	2576	37,000	80,000	154,000	96.8	98.3
Transit 2-B perfect forward section	289,000	1736	21,000	268,000	310,500	99.4	99.4
Transit 2-B acceptable forward section	377,000	1736	28,000	350,000	405,000	99.5	99.6
Courier 1-B perfect forward section	309,000	2576	23,000	286,000	332,000	99.1	99.2
Courier 1-B acceptable forward section	419,000	2576	31,000	388,000	450,000	99.3	99.4

TABLE A-1

RELIABILITIES AND TIME STRESSES FOR SUB-SYSTEMS

			$e^{-T/M}$	T/M	T (sec)	M (sec)
Transit 2-B	Perfect	(Propulsion System	.978	.0221	1736	78,552
		(Forward Section	.994	.0060	1736	289,333
	Acceptable	(Propulsion System	.985	.0150	1736	115,733
		(Forward Section	.995	.0046	1736	377,391
Courier 1-B	Perfect	(Propulsion System	.968	.0323	2576	79,752
		(Forward Section	.992	.0083	2576	308,910
	Acceptable	(Propulsion System	.978	.0220	2576	117,091
		(Forward Section	.994	.0062	2576	418,862

RELIABILITY ANALYSIS OF REDUNDANCY MECHANISMS

by

Nathan Lichter
Grumman Aircraft Engineering Corporation
Bethpage, New York

and

Gilbert Friedenreich
Fairchild Stratos Spacecraft Systems
Bay Shore, New York

17283

Summary

Reliability expressions are derived for two basic functional redundancy techniques as applied to a two-channel system: active redundancy (both channels operate) and standby redundancy (one standby redundancy (one channel operates; the other is switched in upon failure of the first). Each expression is investigated for the effect of the following:

1. Failures of a channel which cause the redundant channel to fail,

2. Failures of a channel which do not effect the redundant channel,

3. Load sharing,

4. Reliability of the switching device.

The equations for each of these methods and their specific parameters are contained in their respective sections. Solutions to these equations have been determined over a wide range of variables using the IBM 7090 computer, and the results are shown graphically in Figures 9 and 11. An analysis of these plots leads to the following observations and conclusions:

1. Active redundancy rather than standby redundancy should be used whenever technically feasible due to its simplicity and reliability potential resulting from load sharing (derating) as noted below.

2. The traditional reliability expression for active redundancy,

$R_{SYSTEM} = 2R_{CHANNEL} - R^2_{CHANNEL}$,

may provide erroneous conclusions since it does not allow for the negative effect of short type failures or the beneficial effect of derating resulting from load sharing between the two active channels. Comparison of this expression with that for standby redundancy assuming perfect decision and switching devices shows that standby redundancy reliability is only slightly greater than active redundancy reliability under these assumptions (Figure 9).

3. As the probability of short failures increases, the reliability of the active redundant system decreases such that when the ratio of short to open failures is unity, system reliability is approximately equal to the reliability of a single channel. System failure resulting from "shorts" can be minimized by the addition of isolation devices in each channel to divorce the failed channel from the system.

4. On the other hand, if the active redundant elements exhibit reduced failure rates because they share the load (derated), system reliability is greater than that obtained from, $R = 2R_C - R_C^2$. Assuming short failures are negligible, active redundancy reliability will exceed standby redundancy, even with perfect switching, when the ratio of open failure rate at half load (derated operating condition) to open failure rate at full load is one half (1/2).

5. The obvious disadvantage of standby redundancy is the complexity resulting from the decision/switching device. An open type failure in this device fails the redundant system, and a rapid deterioration in system reliability results as the open type failure rate increases as shown in Figure 11.

6. Neglecting the open type failure of the switching device, the reliability of the standby redundancy system will always exceed $2R_C - R_C^2$ provided the probability of successful switchover from the failed channel to the standby channel is greater than the reliability of the channel itself.

Introduction

Systems designed for extended missions often apply redundancy when complexity and the inherent part failure rate preclude achieving desired reliability goals. There are various ways of achieving redundancy. In view of limitations on weight and space, it is important that optimum methods be selected, compatible with the design objective.

This paper presents a technique for evaluating two types of redundancy: active, where the

redundant components function continuously; and standby, where the redundant components do not function until a failure occurs, whereupon a switching device replaces the failed component with an operable one. The evaluation is made considering the effects of a number of variables such as short and open type failures, load sharing, and reliability of the switching devices.

Some of these effects have been presented separately in other studies but this paper combines all of these variables into a single set of equations.[3,4] In order to simplify the presentation, the study has been limited to the exponential distribution and second order redundancy. However, the method itself is applicable to multichannel systems with higher order redundancies and for distributions other than the exponential.

The method is useful even when specific failure rates are not available since the curves generated can be applied in a qualitative sense by the systems designer.

Single Channel Reliability

The term "channel" is used in this report to describe a determinate path of flow between two points and may consist of a part, element, group of parts, module, subsystem, or equipment and its connecting hardware. Thus it is assumed that where a channel consists of many parts or elements in series, a failure of any one may interrupt the flow and will contribute to channel failure.

If the failure pattern of the channel can be described by the exponential distribution, the total channel failure rate, λ, is then equal to the sum of the failure rates of the individual parts. Carhart defines the reliability of such a configuration as:[1]

$$R = \exp \left[-\lambda t\right], \tag{1}$$

where

λ = total failure rate of channel, and

t = mission time

Active Redundancy - Independent Channels

When two independent channels, each capable of performing the same task, are both functioning continuously they are considered actively redundant. This situation is portrayed in Figure 1.

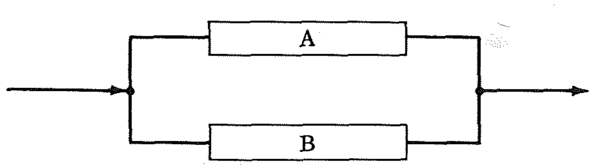


Figure 1

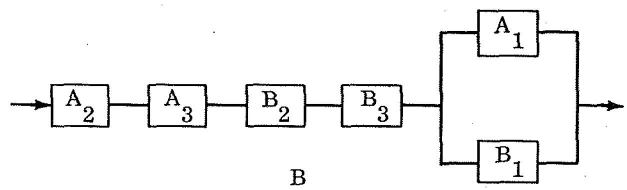
The term "independent" means that the performance, or loss, of one channel has little or no effect on the failure probability of the other. It is not necessary for both channels to be physically installed parallel in order to be functionally parallel in a reliability sense. For example, two check valves, A & B, are installed in series to insure against reverse flow as shown in Figure 2A. There are essentially three modes of failure that can occur to each of these valves:

1. Failure to close when flow reverses.

2. Failure to open when flow commences.

3. External leakage.

A



B

Figure 2

Figure 2B is the reliability block diagram representing the above arrangement, with subscripts 1, 2, and 3 indicating the modes of failure discussed above.

This example was chosen to demonstrate the choice of the term "Active Redundancy" rather than "Parallel Redundancy." The word "parallel" is sometimes misleading, implying physical arrangements and possibly ignores certain modes of failure.

For certain installations, failure modes 2 and 3 are virtually non-existent so that Figure 2B reduces to that portrayed by Figure 1.

The probability of system success can be shown to be:[1]

$$R_T = R_A + R_B - R_A R_B , \tag{2}$$

where

R_A = reliability of channel A, and

R_B = reliability of channel B.

If both channels are identical, or have the same reliabilities, $R_A = R_B = R$, Equation (2) reduces to:

$$R_T = 2R - R^2. \tag{3}$$

Since very few systems will ever approach the ideal independent conditions defined above, Equations (2) & (3) can be considered as theoretical independent active redundancy.

When the exponential distribution is considered applicable, Equation (2) may be rewritten as follows:

$$R_T = \exp\left[-\lambda_A t\right] + \exp\left[-\lambda_B t\right] - \exp\left[-(\lambda_A + \lambda_B)t\right], \qquad (4)$$

where

λ_A = total failure rate of channel A,

λ_B = total failure rate of channel B, and

t = mission time.

If both channels have the same failure rates, $\lambda_A = \lambda_B = \lambda$, Equation (4) reduces to:

$$R_T = 2\exp\left[-\lambda t\right] - \exp\left[-2\lambda t\right]. \qquad (5)$$

Active Redundancy - Dependent Channels

In most cases of active redundancy certain types of failure possibilities exist where the entire system will be affected. If the channels A and B in Figure 1 are electrical in nature, a short or ground type failure in either A or B will result in system failure, whereas an open type failure will not affect system operation. A similar situation can be cited for a hydraulic system. If A and B represent hydraulic pumps, a large leak or pump casing burst will deplete the reservoir and consequently cause complete system failure. It is apparent then that as the ratio of probability of short type to open type failures increases, a point may be reached where active redundancy provides lower reliabilities than a single channel. This ratio is later shown to be approximately unity.

In many applications of active redundancy, the load is actually shared by the two channels where each channel is capable of carrying the entire load. This factor should be considered in estimating the system reliability since numerous equipments exhibit a decrease in failure rate with decreasing load. Thus if channels A and B each carry half the load, the individual channel failure rate may be considerably less than normal, until one fails, whereupon the other takes on the full load at a higher failure hazard.

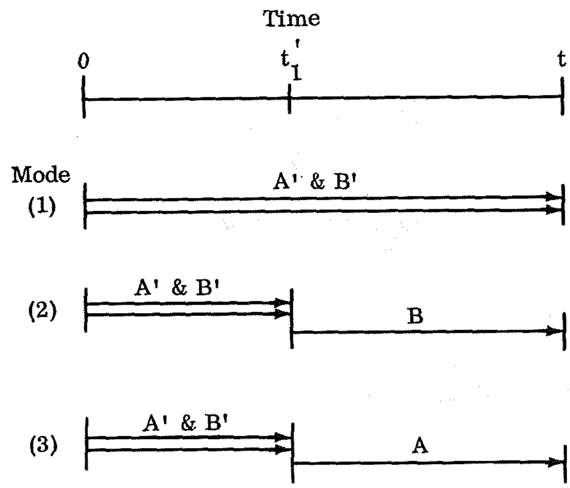
The dependent active redundancy system can be successful in the following modes of operation.

$P_{(1)}$ Both channels, A and B, each carrying half load, function successfully until time t.

$P_{(2)}$ Both channels, A and B, each carrying half load, function successfully until time t_1', where A fails - due to an open type failure, and B continues to function at full load until time t.

$P_{(3)}$ Same as $P_{(2)}$, except B fails and A continues to function.

The following diagram, Figure 3, represents these successful modes.



where: A' = operation of A at half load.
B' = operation of B at half load.
A = operation of A at full load.
B = operation of B at full load.
t_1' = time to first channel failure.

Figure 3

Mathematically, the probability of these occurences may be expressed as follows:

$$P_{(1)} = R_A' R_B', \qquad (6)$$

where

R_A' = probability that channel A does not fail for any reason at half load during time interval 0 to t, and

R_B' = Probability that channel B does not fail for any reason at half load during time interval 0 to t.

$$P_{(2)} = (1-R_{Ao}')R_{At_1's}' R_{Bt_1'}' R_B/R_{Bt_1'}, \qquad (7)$$

where

$(1-R_{Ao}')$ = probability that channel A fails to open at half load during time interval 0 to t,

$R'_{At'_1s}$ = probability that channel A does not fail due to a short type failure at half load during time interval 0 to t'_1,

$R'_{Bt'_1}$ = probability that channel B does not fail for any reason at half load during time interval 0 to t'_1, and

$R_B/R_{Bt'_1}$ = probability that channel B does not fail for any reason at full load during time interval t'_1 to t,

where

R_B = probability that channel B does not fail for any reason at full load during time interval 0 to t, and

$R_{Bt'_1}$ = probability that channel B does not fail for any reason at full load during time interval 0 to t'_1.

$$P_{(3)} = (1-R'_{Bo})\, R'_{Bt'_1s}\, R'_{At'_1}\, R_A/R_{At'_1} \quad , \qquad (8)$$

where the definitions for Equation (7) apply except that the channel identification reverses, since B fails and A continues functioning.

Therefore, the probability of success of an active redundant system will be the summation of the probability of success of each of the above possible modes of operation, or:

$$\begin{aligned} R_T &= P_{(1)} + P_{(2)} + P_{(3)} \\ &= R'_A R'_B + (1-R'_{Ao})R'_{At'_1s}\, R'_{Bt'_1}\, R_B/R_{Bt'_1} \\ &\quad + (1-R'_{Bo})\, R'_{Bt'_1s}\, R'_{At'_1}\, R_A/R_{At'_1} \qquad (9) \end{aligned}$$

In many applications channels A and B can be assumed to be identical. Therefore $R'_A = R'_B = R'$, $R'_{At'_1} = R'_{Bt'_1} = R'_{t'_1}$, $R'_{Ao} = R'_{Bo} = R'_o$, $R'_{At'_1s} = R'_{Bt'_1s} = R'_{t'_1s}$, $R_A = R_B = R$ and $R_{At'_1} = R_{Bt'_1} = R_{t'_1}$.

Substituting these values in Equation (9) and simplifying yields:

$$R_T = R'^2 + 2RR'_{t'_1}\, R'_{t'_1s}\, (1-R'_o)/R_{t'_1} \qquad (10)$$

If the channels of the system under analysis do not reflect a change in the probability of success with changing load, then $R = R'$, $R_{t'_1} = R'_{t'_1}$, $R_o = R'_o$ and $R_{t'_1s} = R'_{t'_1s}$.

$$R_T = R^2 + 2RR_{t'_1s}\,(1-R_o) \qquad (11)$$

Now if there is no possibility of short type failures, $R_{t'_1s} \rightarrow 1$ and $R_o \rightarrow R$, Equation (11) reduces to $R_T = 2R-R^2$, which is the same as Equation (3) for independent active redundancy. Thus Equation (3) is the special case of Equation (9) where the channels are identical and the performance of either channel is completely independent of the other.

Exponential Failure Pattern

Assuming that the failure pattern of the channels is exponential, Equation (10) can be rewritten as follows:

$$\begin{aligned} R_T &= \exp\left[-2\lambda' t\right] \\ &\quad + 2\exp\left[-(\lambda' + \lambda'_s - \lambda)t'_1 - \lambda t\right] \\ &\quad \left(1 - \exp\left[-\lambda'_o t\right]\right), \qquad (12) \end{aligned}$$

where

λ'_o = failure rate for open failures of either channel at half load,

λ'_s = failure rate for short failures of either channel at half load,

λ' = total failure rate of either channel at half load, $\lambda' = \lambda'_o + \lambda'_s$,

λ = total failure rate of either channel at full load,

t = mission time, and

t'_1 = time at which primary channel fails.

Before Equation (12) may be applied, an estimate of t'_1 must be made since it is usually the only parameter not normally available.

The exponential failure pattern of the channel is shown in Figure 4.

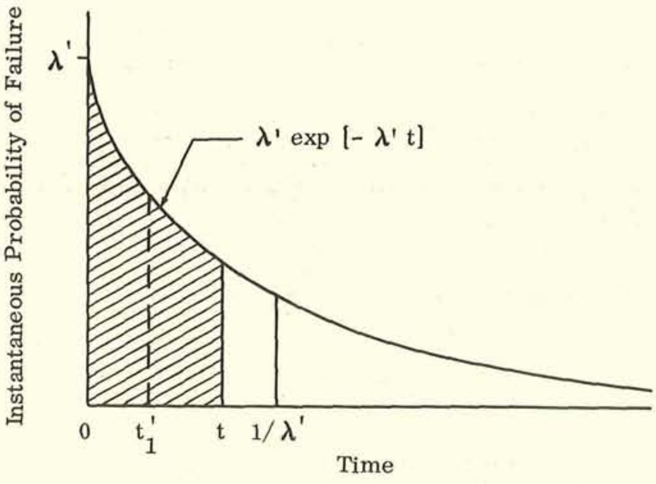


Figure 4

The mission time, t, should usually be substantially less than $1/\lambda'$, the mean-time-between-failures. The expected value of t_1' will be the mean of the shaded area under the probability density function (Figure 4) or:

$$E(t_1') = \frac{\int_0^t t(\lambda' \exp\left[-\lambda' t\right])dt}{\int_0^t \lambda' \exp\left[-\lambda' t\right]dt} \qquad (13)$$

Solving Equation (13) for the expected value of the time at which the primary channel fails yields:

$$E(t_1') = \frac{1}{\lambda'} - \frac{t \exp\left[-\lambda' t\right]}{1-\exp\left[-\lambda' t\right]} \qquad (14)$$

or

$$E(t_1') = \frac{1}{\lambda'} - \frac{t}{\exp\left[\lambda' t\right] - 1} \qquad (15)$$

If the same assumption is made as in the derivation of Equation (11) where the channels of the system under analysis do not reflect a change in probability of success with changing load, then $\lambda = \lambda'$, $\lambda_o = \lambda_o'$ and $\lambda_s = \lambda_s'$. Substituting into Equation (11) and simplifying the results:

$$R_T = \exp\left[-2\lambda t\right] + 2\exp\left[-\lambda_s t_1' - \lambda t\right] (1 - \exp\left[-\lambda_o t\right]) \qquad (16)$$

Note that the prime in t_1' is retained since t_1' is also based upon open failures. It is shown later that t_1, the expected time at which the primary channel of a standby redundant system fails, is a function of both open and short type failures.

Again assuming that there is no possibility of short type failures, $\lambda_s \rightarrow o$, and Equation (16) reduces to:

$$R_T = 2\exp\left[-\lambda t\right] - \exp\left[-2\lambda t\right] \qquad (17)$$

Equation (17) is identical to Equation (5) again proving that the assumption of active redundancy with independent channels is only a special case of active redundancy with dependent channels.

Comparison Of Independent And Dependent Active Redundancy Equations

Graphic Comparison

System reliabilities computed for various combinations and values of failure rate substituted in Equation (16) are plotted against total channel failure rate in Figure 9. The effects of short type failures, $\lambda_s > o$, and reduced open failure rate with shared loads, $\lambda_o'/\lambda_o < 1$, are shown for a 1 year mission compared with the reliability of the independent active redundant system.

The curves in Figure 9 result from repetitive solutions of the applicable equations utilizing the facilities of an IBM 7090 digital computer.

It can be seen that as the probability of short type failures increases, the reliability of the system decreases below the curve representing a theoretical independent active redundant system, when $\lambda_s/\lambda_o = 1$, system reliability is approximately equal to channel reliability. Conversely, if the equipment exhibits reduced open failure rates because the load is shared between the two channels, $\lambda_o'/\lambda_o < 1$, system reliability increases above the theoretical curve and may exceed a standby redundant system with perfect switching, which is discussed in detail in the following section.

Analytic Comparison

Since it has been shown that $\lambda = \lambda_o + \lambda_s$, Equation (16) may be rewritten:

$$R_T = \exp\left[-2(\lambda_o + \lambda_s)t\right] + 2\exp\left[-\lambda_s t_1' - (\lambda_o + \lambda_s)t\right] (1 - \exp\left[-\lambda_o t\right]) \qquad (18)$$

By rearranging this equation and comparing the result with Equation (5), a qualitative comparison may be made between estimates of system reliability based upon independent and dependent redundancy. Equation (18) becomes:

$$R_T = 2\exp\left[-\lambda_o t\right] \exp\left[-\lambda_s(t_1' + t)\right] - \exp\left[-2\lambda_o t\right] \left\{2\exp\left[-\lambda_s(t_1' + t)\right] - \exp\left[-2\lambda_s t\right]\right\} \qquad (19)$$

Obviously $t_1' < t$ (see Figure 4). It follows then that $\exp\left[-\lambda_s(t_1' + t)\right] > \exp\left[-2\lambda_s t\right]$ and that $\left\{2\exp\left[-\lambda_s(t_1' + t)\right] - \exp\left[-2\lambda_s t\right]\right\}$ is positive and also greater than $\exp\left[-\lambda_s(t_1' + t)\right]$. The first term of Equation (19) is smaller than the first term of Equation (5) by the factor $\exp\left[-\lambda_s(t_1'+t)\right]$ and although the second term of Equation (19) is smaller than that of Equation (5), it does not diminish as rapidly as the first term since $\left\{2\exp\left[-\lambda_s(t_1'+t)\right] - \exp\left[-2\lambda_s t\right]\right\} > \exp\left[-\lambda_s(t_1'+t)\right]$. Therefore using the estimate of system reliability based upon dependent redundancy, Equation (19), is always less than that obtained by basing the estimate upon independent redundance, Equation (5).

The preceding discussion proves that where short type failures are possible, the use of Equations (2) through (5) will lead to optimistic solutions.

Further, it will now be shown that it is possible for a redundant system to be worse than a single channel. Another rearrangement of Equation (16) yields:

$$R_T = \exp\left[-\lambda t\right]\left\{\exp\left[-\lambda t\right] + 2\exp\left[\lambda_s t_1'\right]\left(1-\exp\left[-\lambda_o t\right]\right)\right\} \quad (20)$$

But $\exp\left[-\lambda t\right] = R$, the channel reliability, then

$$R_T = R\left\{R + 2\exp\left[\lambda_s t_1'\right]\left(1-\exp\left[-\lambda_o t\right]\right)\right\} \quad (21)$$

It is obvious then, that when

$$\left\{R + 2\exp\left[\lambda_s t_1'\right]\left(1-\exp\left[-\lambda_o t\right]\right)\right\} > 1,$$

then $R_T > R$;

and

$$\left\{R + 2\exp\left[\lambda_s t_1'\right]\left(1-\exp\left[-\lambda_o t\right]\right)\right\} = 1,$$

then $R_T = R$;

and when

$$\left\{R + 2\exp\left[\lambda_s t_1'\right]\left(1-\exp\left[-\lambda_o t\right]\right)\right\} < 1,$$

then $R_T < R$.

Example

A typical square wave oscillator power supply, A, is shown in Figure 10. To improve reliability, a second power supply, B, has been placed in active dependent redundancy. The circuits have been modified to insure that no component part, failing short, would result in a system failure. This was done to take full advantage of the active redundancy with derated channels.

Equation (12) may now be used to estimate the system reliability. It should be recognized that $\lambda'_s = 0$ and that λ' represents the total channel failure rate at half load $\lambda'_o = \lambda'$. An assumption is made that the fuse will always open the circuit upon an equipment short type failure. If this assumption cannot be considered valid, the system reliability would be estimated by the method discussed later in the section on Dependent Active Redundancy With Isolation Devices.

The failure rates used for this example are shown in Table I for both 100% and 50% rated output. For a mission time of one year, the reliability, R, of each power supply channel, is 0.8717. When applying Equation (12), the system reliability is found to be 0.9877.

If the classical equation, referred to a independent active redundancy, equation (3), was used, the system reliability would be estimated to be .9835. This does not appear to be significantly different from the estimate from Equation (12). However, when examining the unreliability, Q, where $1 = R + Q$, it can be seen that the estimate of this probability of failure has been increased 34%.

Standby Redundancy

Figure 5 is a schematic of a two-channel system in standby redundancy. Note that the secondary channel (B), is completely isolated from the primary channel (A), by a decision making device (D) and a switching device (S). The secondary channel does not perform any function unless the primary fails, and the secondary channel is successfully switched into the system.

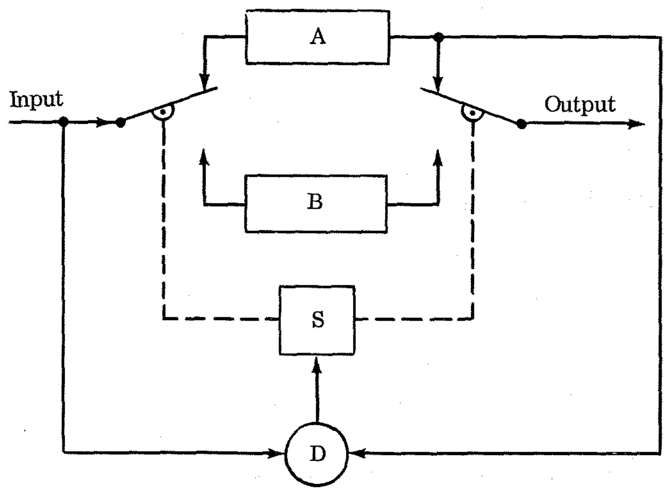


Figure 5

An example would be two amplifiers connected in parallel. When the output of A falls outside the acceptable tolerance limits, the decision device triggers the switch relay to replace channel A with channel B to maintain system operation. Two switches are not absolutely necessary to accomplish this task, but serve to show the complete isolation of channel B from A. Depending on the function of the system and the circuitry, the second switch may be replaced by other means of isolation, such as two diodes as shown in Figure 6.

The schematics in Figures 5 and 6 portray circuitry that is irreversible. That is, once the decision device has required switch-over, either by failure of the primary channel or by failure of the decision making and/or switching device, it cannot reselect the primary channel. The consideration of systems including reversible decision devices is beyond the scope of this paper.

The assumptions made or implied in the preceding paragraphs are summarized below to facilitate the analysis.

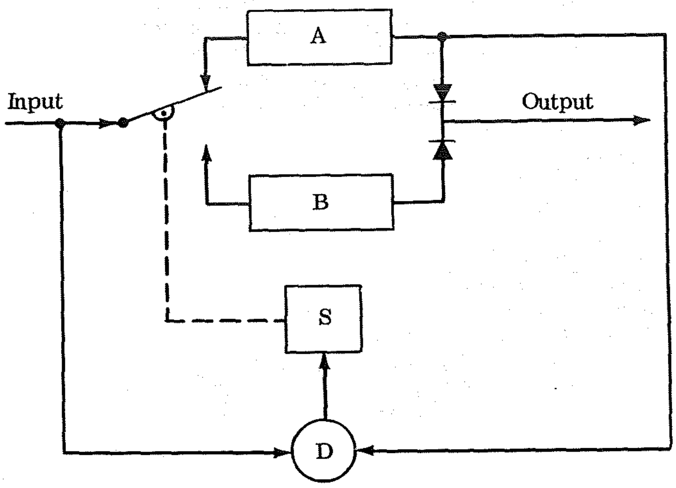


Figure 6

1. The channels are isolated such that a failure in one cannot cause failure in another.

2. The standby channel is not affected by the environment, i.e., the failure rate before operation is negligible compared to the failure rate during operation.

3. The decision-switching device is irreversible.

An examination of the above schematics also indicates that the decision device, which may consist of a detector or monitor and a comparitor can be considered in series with the switch from a reliability standpoint. Therefore, the term "switching device" will hereafter include all of these items.

The system appearing in Figure 5 can be successful in the following modes of operation.

$P_{(1)}$ The primary channel, A, operates successfully up to time t. The switching device is successful, i.e., does not make a false decision, to time t.

$P_{(2)}$ The primary channel fails at time t_1. The switching device, not having made a false decision, replaces the primary channel with the secondary channel, B, which operates successfully to time t.

$P_{(3)}$ The primary channel operates until the switching device makes a false decision, at time t_2, connecting the secondary channel, which operates successfully to time t.

The following diagram, Figure 7, illustrates these three successful modes.

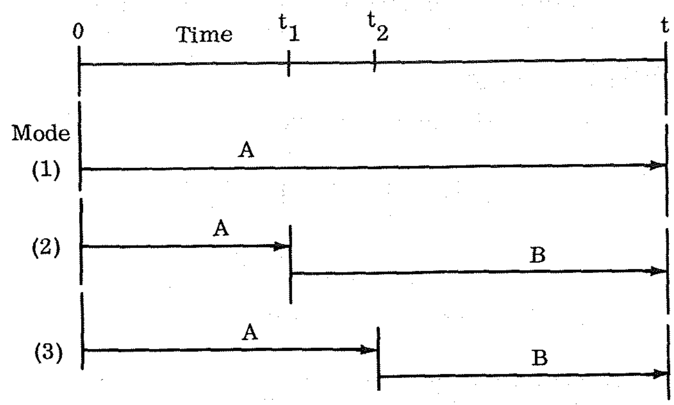


Figure 7

Mathematically, the probabilities of these occurrences can be expressed as follows:

$$P_{(1)} = R_A R_{SW}, \tag{22}$$

where

R_A = probability that channel A does not fail for any reason during time interval 0 to t, and

R_{SW} = probability that switch does not make a false decision during time interval 0 to t.

$$P_{(2)} = (1-R_A)\ R_{SRt_1}\ R_B/R_{Bt_1}, \tag{23}$$

where

$(1-R_A)$ = probability that channel A does fail for any reason during time interval 0 to t,

R_{SRt_1} = probability that switch has not made a false decision prior to t_1, R_{SWt_1}, and then operates successfully when channel A fails at time t_1, R_{SFt_1}, or $R_{SRt_1} = R_{SWt_1} \cdot R_{SFt_1}$. It is not necessary for the switch to operate after t_1,

R_B/R_{Bt_1} = probability that channel B does not fail for any reason during time interval t_1 to t,

where

R_B = probability that channel B does not fail for any reason during time interval 0 to t, and

R_{Bt_1} = probability that channel B does not fail for any reason during time interval 0 to t_1.

$$P_{(3)} = (1-R_{SW})\, R_{At_2} R_B/R_{Bt_2}\,, \qquad (24)$$

where

$(1-R_{SW})$ = probability that switching device will make a false decision at time t_2, during the time interval 0 to t.

R_{At_2} = probability that channel A functions successfully until false decision by switch at time t_2. After t_2, it does not matter whether channel A is capable of functioning or not.

R_B/R_{Bt_2} = probability that channel B does not fail for any reason during time interval t_2 to t,

where

R_B = probability that channel B does not fail for any reason during time interval 0 to t, and

R_{Bt_2} = probability that channel B does not fail for any reason during time interval 0 to t_2.

The probability of system success will be the summation of the probability of success of each of the above modes of operation, or:

$$\begin{aligned} R_T &= P_{(1)} + P_{(2)} + P_{(3)} \\ &= R_A R_{SW} + (1-R_A)\, R_{SRt_1} R_B/R_{Bt_1} \\ &\quad + (1-R_{SW}) R_{At_2} R_B/R_{Bt_2} \qquad (25) \end{aligned}$$

This equation <u>does not</u> include the probability of switch contacts <u>failing</u> open. This approach is considered reasonable since it is feasible to design equipment where the probability of this type failure is highly remote. In cases where this type failure cannot be eliminated, Equation (25) is modified as follows to include this factor:

$$\begin{aligned} R_{TT} &= R_{SO} R_T \\ &= R_{SO}\Big[R_A R_{SW} + (1-R_A)\, R_{SRt_1} R_B/R_{Bt_1} \\ &\quad + (1-R_{SW})\, R_{At_2} R_B/R_{Bt_2}\Big], \qquad (26) \end{aligned}$$

where

R_{SO} = probability that the switch will not fail open during the time interval 0 to t. (Note that a further examination of Figure 6 reveals that a failure caused by an open contact of the relay would appear to the switching device as an open failure in channel A. The switch would then initiate the relay to energize channel B. It would appear, therefore, only necessary to consider the open contact type of the relay from time t_1 to t. The choice of the time interval is dependent upon the exact design of the switching device.)

Equation (25) can be considered a special case of Equation (26) where $R_{SO} = 1$. Obviously $R_{TT} \leqq R_T$ since $R_{SO} \leqq 1$. Therefore, it is evident that the switching device should be designed so that $R_{SO} \to 1$.

In many cases of standby redundancy, channels A and B are identical and capable of performing the same function. Under these conditions $R_A = R_B = R$, $R_{At_1} = R_{Bt_1} = R_{t_1}$ and $R_{At_2} = R_{Bt_2} = R_{t_2}$. Substituting these values in Equation (25) and rearranging yields:

$$R_T = R\left[1 + (1-R)\, R_{SRt_1}/R_{t_1}\right] \qquad (27)$$

The following observations should be noted:

1. The terms involving t_2 (time at which the switching device makes a false decision) drops out of the equation. This indicates that the reliability of a standby redundant system with two identical channels is independent of the time at which the switching device makes a false decision.

Although the term R_{SW} (probability of no false decision) has also dropped out of the equation, it is related to the term R_{SRt_1} where $R_{SR} = R_{SW} \cdot R_{SF}$, see Equation (23). Thus successful operation is equally dependent on both the decision device not making a false decision and the decision device functioning satisfactorily upon failure of the first channel.

2. The reliability of the standby redundant system will never be less than that of a single channel, i.e., $R_T > R_1$ since $\left[1 + (1-R)\right] > 1$ because R is always less than unity. This is true, regardless of the value of the probability of sucessful switch-over, since $R_{SRt_1}/R_{t_1} \to 0$ only when $R_{SRt_1} \to 0$. (Note that these conclusions neglect the possibility of open type switch failures, i.e., $R_{SO} \to 1$).

3. For standby redundancy to be more reliable than theoretical independent active redundancy, the probability of successful switch-over must be greater than the reliability of an indi-

vidual channel, $R_{SR} > R$. This statement is proved as follows: If $R_{SR} = R$, then $R_{SRt_1}/R_{t_{1_2}} = 1$, and equation (27) then reduces to $R_T = 2R-R^2$ which is equation (3), theoretical independent active redundancy. (However, recall that equation (3) does not include the possibility of short type failures and assumes $R = R_o$. Also, again note the assumption that $R_{SO} \longrightarrow 1$).

It was shown previously that if short type failures are possible and the equipment under consideration does not reflect increases in reliability with reduced load, the reliability of an active redundant system will be less than that expressed by Equation (3), $R_T < 2R-R^2$. Therefore it is concluded that under these conditions, standby redundancy will yield improved results over active redundancy as long as $R_{SR} > R$ and $R_{SO} \longrightarrow 1$.

Exponential Failure Pattern

If the failure pattern of the channels and the switch is assumed to be exponential, Equation (25) may be rewritten:

$$R_T = \exp\left[-(\lambda_A + \lambda_{SW})\, t\right] + \left(1-\exp\left[-\lambda_A t\right]\right) \exp\left[-\lambda_{SR} t_1\right] \exp\left[-\lambda_B\,(t - t_1)\right] + \left(1-\exp\left[-\lambda_{SW} t\right]\right) \exp\left[-\lambda_A t_2\right] \exp\left[-\lambda_B\,(t - t_2)\right], \qquad (28)$$

where

λ_A = total failure rate of channel A,

λ_B = total failure rate of channel B,

λ_{SW} = failure rate of switching device making a false decision,

λ_{SR} = total failure rate of switching device $= \lambda_{SWt} + \lambda_{SF}$

where

λ_{SF} = failure rate of switching device not operating properly when required,

t = mission time,

t_1 = time at which channel A fails, and

t_2 = time at which false decision is made by switching device.

When channel A is identical to channel B, $\lambda_A = \lambda_B = \lambda$. Substituting into Equation (28) yields:

$$R_T = \exp\left[-\lambda t\right] \left\{ 1+\left(1-\exp\left[-\lambda t\right]\right) \exp\left[-(\lambda_{SR} - \lambda) t_1\right] \right. \qquad (29)$$

Before Equation (29) may be applied, it will be necessary to determine the value of t_1, the expected time at which the primary channel fails.

The expected value of t', has been derived in Equations (14) and (15). In this application however, the failure of the primary channel is based upon the total failure rate at full load rather than open failures at half load. Therefore $E(t_1)$ is:

$$E\,(t_1) = \frac{1}{\lambda} - \frac{t}{\exp\left[\lambda t\right] - 1} \qquad (30)$$

Substituting the expected value of t_1 into Equation (29) provides the most useful form for comparitive studies.

$$R_T = \exp\left[-\lambda t\right] \left\{ 1 + \left(1-\exp\left[-\lambda t\right]\right) \exp\left[-(\lambda_{SR}-\lambda)\left(\frac{1}{\lambda} - \frac{t}{\exp\left[\lambda t\right] - 1}\right)\right] \right. \qquad (31)$$

Comparison of Active And Standby Redundancy Equations

Graphic Comparison

Figure 9 shows that for a mission time of 1 year, where short type failures are not possible, $\lambda'_s = \lambda_s = 0$, active redundancy can exceed standby redundancy with perfect switching when the ratio of channel failure rate at half load to full load is one half, $\lambda'/\lambda = 1/2$.

Therefore, in the general case, where short type failures are possible and the equipment exhibits reduction of failure rate with reduced load, it will be necessary to solve both Equations (12) and (29) to determine which type of redundancy will provide the highest reliabilites.

Figure 11 shows the effects of switching reliabilities on system reliability for a one year mission and compares standby redundancy against independent active redundancy and single channel reliability. Curve 1 is the maximum reliability obtainable with a standby redundant system since perfect switching is employed. Curves 2, 3, and 4 show the rapid degradation of system reliability as switching device failures are introduced. However, curve 2 illustrates that if the switching device cannot fail open, reasonable improvement is made over single channel reliability even with low probability of successful switchover and curve 4 demonstrates that it cannot be worse than single channel reliability.

Now where even the slight possibility of open type failure of the switching device exists, as shown in curve 3, considerable reduction of system reliability occurs, especially in the area of low channel failure rates. The low failure rates portrayed in the abscissa

of Figure 11 imply very simple channels and thus even low failure rates of the switching device of curve 3 will indicate poor system reliabilities. It should be apparent then that standby redundancy can be better justified where more complicated equipment (those having higher failure rates) are employed.

Note also that if the second assumption for the configuration in Figure 6 is not entirely valid, the standby redundant system reliability as computed by Equations (27) and (31) may be slightly optimistic. However, a degree of conservatism can be obtained by assuming a small increase in the basic failure rate of the channel when applying the standby redundancy equation.

Analytic Comparison

If equipment exhibits a reduction in failure rate with reduced load, it is possible that the reliability of an active redundant system can exceed the reliability of a standby redundant system even if 100% perfect switching is employed. To prove this, the possibility of short type failures are neglected, $\lambda_s \rightarrow 0$, $\lambda'_s \rightarrow 0$.

Equation (12) for dependent active redundancy reduces to:

$$R_T = \exp\left[-2\lambda' t\right] + 2\left(1 - \exp\left[-\lambda' t\right]\right) \exp\left[-(\lambda' - \lambda)\, t_1'\right] \exp\left[-\lambda t\right] \qquad (32)$$

and assuming perfect switching, $\lambda_{SR} \rightarrow 0$, for equation (29) yields:

$$R_T = \exp\left[-\lambda t\right] + \left(1 - \exp\left[-\lambda t\right]\right) \exp\left[\lambda t_1\right] \exp\left[-\lambda t\right] \qquad (33)$$

The first term of Equation (32) will be greater than the first term of Equation (33) when $\lambda' < (\lambda/2)$. The second term of Equation (32) can be greater than that of Equation (33) since $\lambda' \leqq \lambda$, $t_1' < t$ and $\exp\left[-(\lambda' - \lambda)\, t_1'\right]$ is always positive, i.e., $2(1 - \exp\left[-\lambda' t\right]) \exp\left[-(\lambda' - \lambda) t_1'\right]$ can be less than or greater than $(1 - \exp\left[-\lambda t\right])$ $\exp\left[\lambda t_1\right]$ depending on the relative values of λ and λ'. It also follows that as $\lambda' \rightarrow 0$, Equation (32) approaches unity for any value of λ, where $0 \leqq \lambda \leqq \infty$

Example

Consider once again the square wave oscillator power supply, Figure 10, used as the example for active redundancy. In this application the same power supply channels are connected in a standby redundant configuration, similar to that shown in Figure 6.

Data collected by the Reliability Control Section at Grumman Aircraft Engineering Corporation has shown that a realistic estimate of the total failure rate of the switch electronics, λ_{SR}, is 1.51×10^{-6}. In addition, the design of the device is assumed to be such that any type of failure will activate the switching relay and also that the relay is designed so that the probability of an open contact is extremely remote. Thus Equation (29) applies.

Substituting λ, from Table I, into this equation results in a standby redundant system overall reliability, R_T, equal to 0.9905 as compared to 0.9877 for active dependent redundancy. In other words, if the assumptions made have been correct, the standby configuration shows a slight improvement over the active redundant system. Of course, in making a decision as to the type of configuration to recommend, consideration must be given to such parameters as wear out, maintainability, availability, etc.

Dependent Active Redundancy - With Isolation Device

The previous discussions indicate that the systems designer should attempt to use active redundancy whenever the equipment exhibits reduced failure rates with reduced load. Such systems are usually lighter and simpler, when technically feasible. However, further increase in system reliability may result from the addition of isolation devices in each of the redundant channels to prevent an equipment short from failing both channels and draining the power supply.

Figure 8 illustrates a two-channel active redundant system with isolation devices. When a short occurs in one of the equipments, the switching device isolates the channel from the system permitting the surviving channel to pick up the full load to continue system operation.

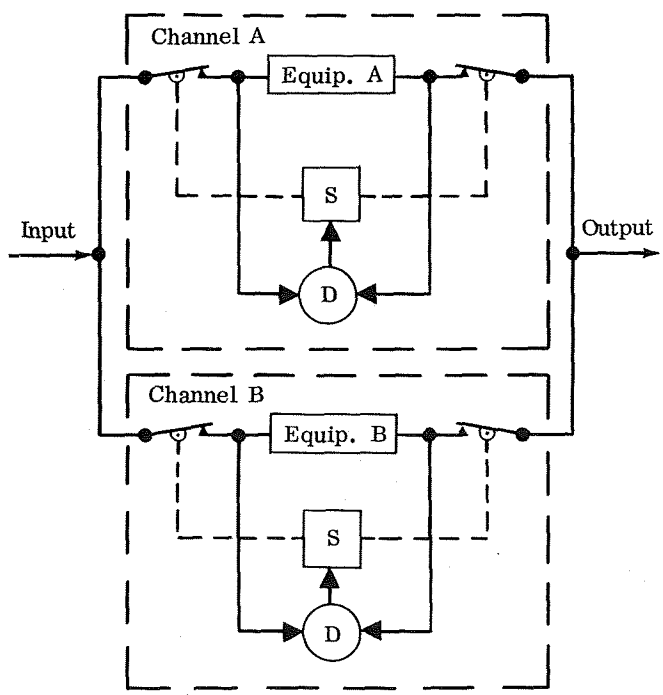


Figure 8

The reliability of an active redundant system with isolation devices is expressed by the same equation developed for the active redundant system less the isolation devices (Equation 12) except that the terms in the equation are interpreted as indicated below to fit this application. Equation (12) is repeated here for convenience:

$$R_T = \exp\left[-2\lambda' t\right] + 2\exp\left[-(\lambda' + \lambda_s' - \lambda)t_1' - \lambda t\right]$$
$$(1 - \exp\left[-\lambda'_o t\right]),$$

where

λ_s = equipment "short" failure rate at full load,

λ_o = channel "open" failure rate at full load,

= equipment "open" failure rate + isolation device (switch) "open" failure rate + inadvertent switch-over failure rate, or

$= \lambda_{Equip._o} + \lambda_{SO} + \lambda_{SW},$

λ = total channel failure rate at full load,

$= \lambda_s + \lambda_o$,

t = mission time,

$$t_1' = \frac{1}{\lambda'} - \frac{t}{\exp\left[\lambda' t\right] - 1},$$

λ_o' = channel "open" failure rate at half load,

= equipment "open" failure rate + isolation device (switch) "open" failure rate + inadvertent switch-over failure rate, or

$= \lambda'_{Equip.} + \lambda_{SO} + \lambda_{SW}$

λ'_s = channel failure rate at half load resulting from both an equipment "short" failure and the inability of the switching device to open the circuit to isolate the shorted equipment from the system and is:

$\approx t \times \lambda'_{s_1} \times \lambda_{SF},$

where

λ'_{s_1} = equipment short failure rate at half load, and

λ_{SF} = isolation device failure rate (not functioning when required),

λ' = total channel failure rate at half load

$= \lambda_o' + \lambda_s'$

The probability (P) that a channel will not fail due to an equipment short failure is a function of the short failure probability and the probability that the isolation device will successfully open the shorted circuit immediately following the short. Using equation (4) to express the joint probability, P, that either event will be successful:

$$P = \exp\left[-\lambda'_s t\right] = \exp\left[-\lambda'_{s_1} t\right] + \exp\left[-\lambda_{SF} t\right] - \exp\left[-(\lambda'_{s_1} + \lambda_{SF})\, t\right] \quad (34)$$

Rearranging terms, Equation (34) becomes

$$P = \exp\left[-\lambda'_s t\right] = 1 - (1 - \exp\left[-\lambda'_{s_1} t\right])\,(1 - \exp\left[-\lambda_{SF} t\right]) \quad (35)$$

It has been shown in the literature that the approximate solution of exp [-x] where, exp [-x] $\approx$ 1-x, introduces very little error when the value of the exponent is small $(x \leq 0.3)$.[1,2] If it is assumed that the exponents in the above equation are within the acceptable range, then the equation may be rewritten:

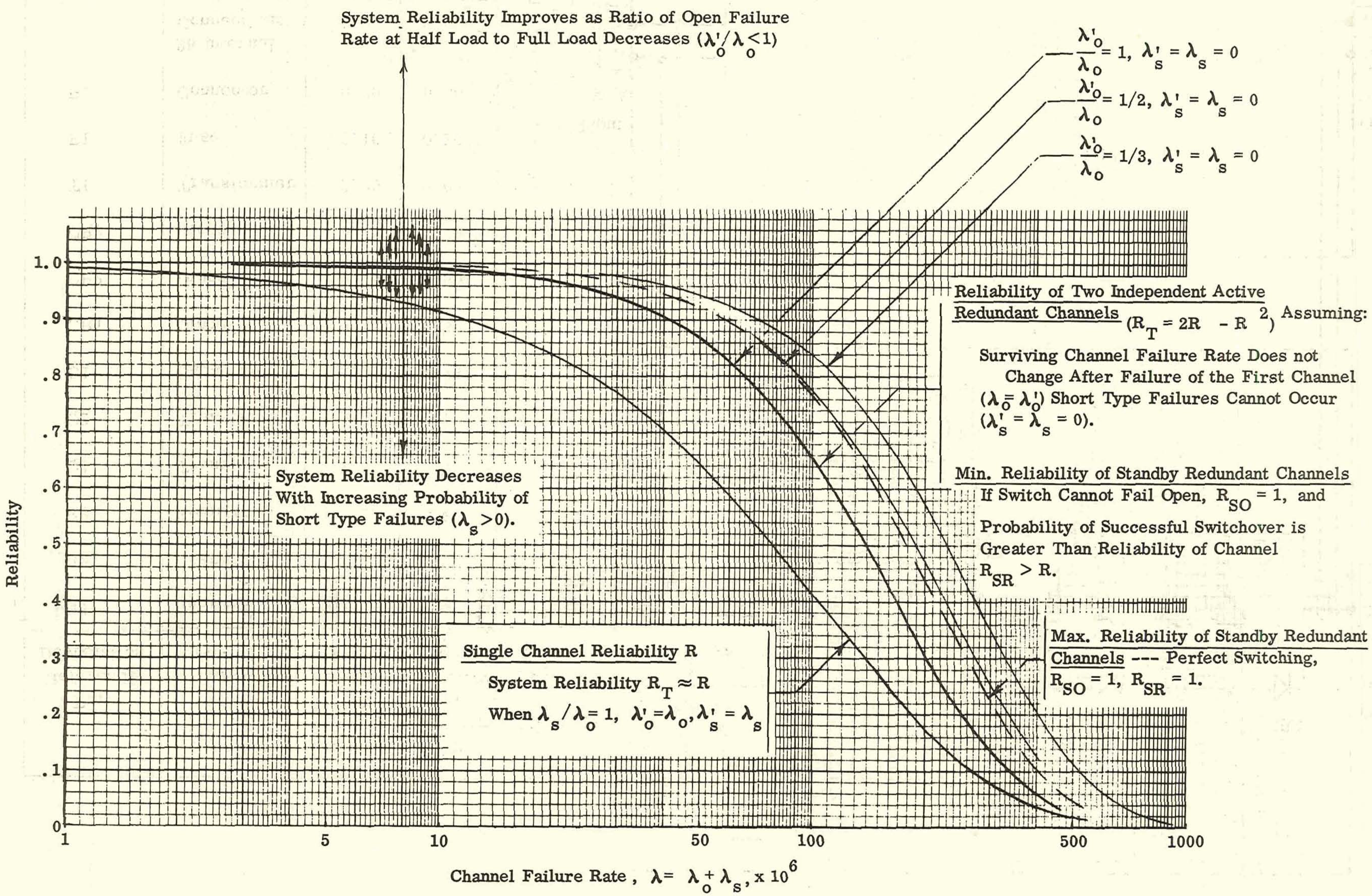
$$1 - \lambda'_s t \approx 1 - (\lambda'_{s_1} t)\,(\lambda_{SF} t) \quad (36)$$

$$\lambda'_s \approx \lambda'_{s_1} \lambda_{SF} t \quad (37)$$

A comparison of the reliability equations for active redundancy with and without isolation devices indicates that no general statement of trend can be made as to which is the better from the reliability viewpoint. The comparison must be made for a specific application on the basis of the detail design of the redundant arrangement and considering complexity, weight, and ease of checkout.

Figure 9 - Reliability of Active Redundant - Two Channel Systems

Mission Time t = 1 Year (8, 760 hours)



Part Reference Designation	Part Type	Failure Rate x 10^6	
		100% Rated Output	50% Rated Output
R1	Resistor	1.90	1.27
R2	Resistor	1.90	1.27
R3	Resistor	1.90	1.27
Q1	Transistor	1.00	0.70
Q2	Transistor	1.00	0.70
C1	Capacitor	1.74	1.74
CR1	Diode	0.75	0.50
CR2	Diode	0.75	0.50
CR3	Diode	0.75	0.50
T1	Transformer	3.00	2.00
F1	Fuse	0.10	0.10
P	Connector	0.60	0.60
	28 Internal Connections	0.28	0.28
Totals	λ	15.67	-
	λ'	-	11.43

TABLE I

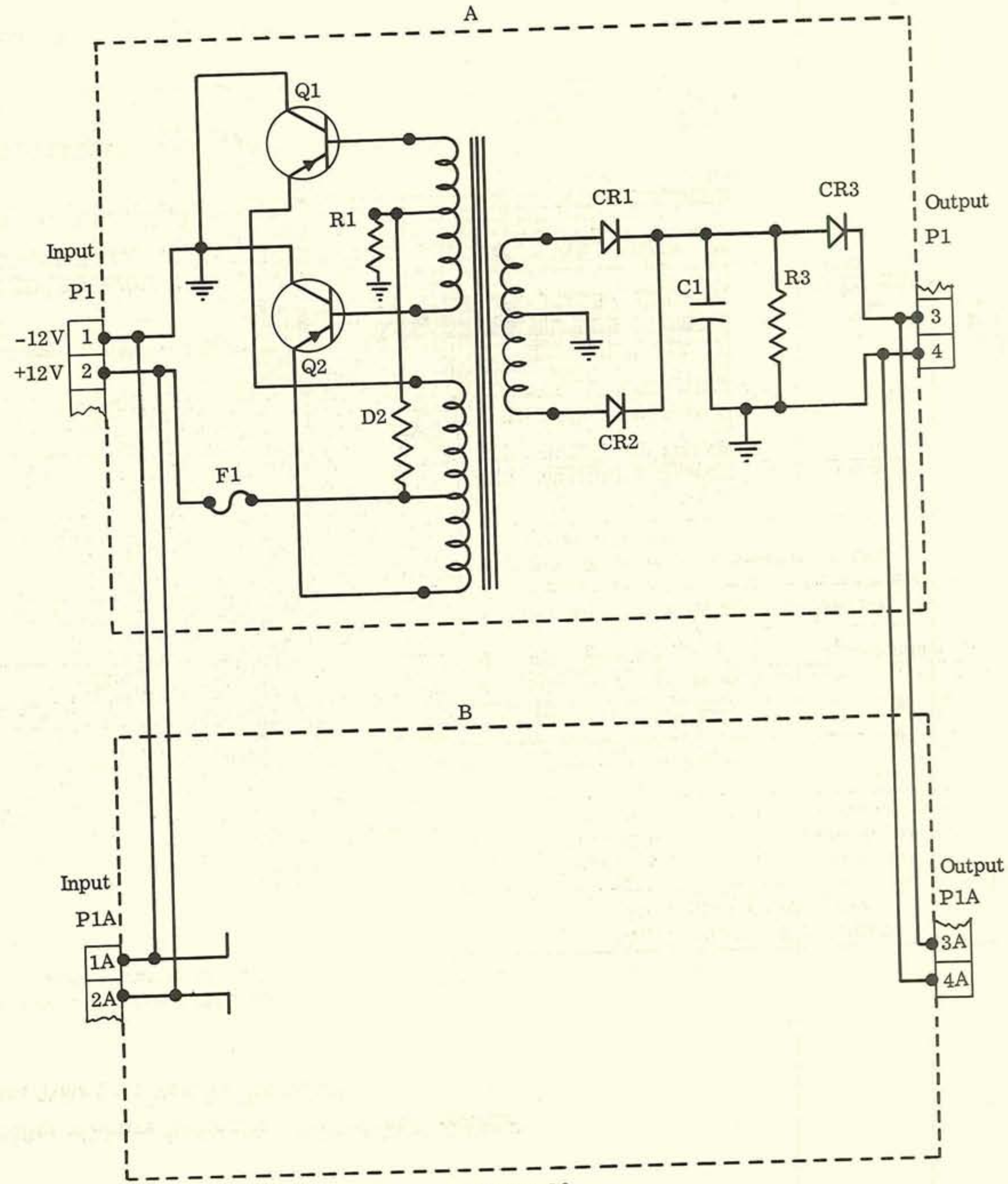
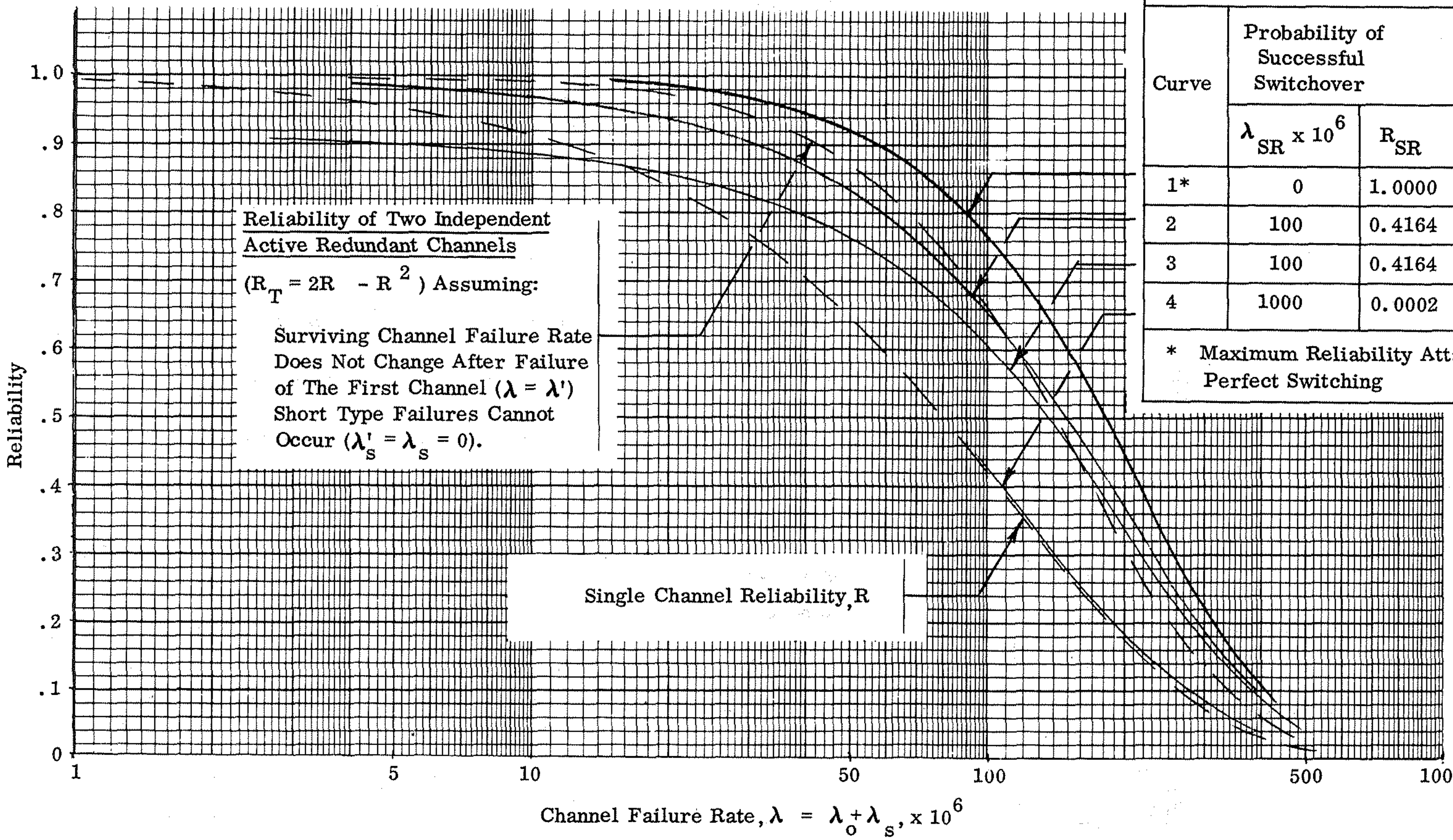


Figure 10

Figure 11 - Reliability of Standby Redundant - Two Channel Systems

Mission Time t = 1 Year (8, 760 hours).



RELIABILITY OF STANDBY REDUNDANT CHANNELS

Curve	Probability of Successful Switchover		Probability of Switching Device Not Failing Open	
	λ_{SR} x 10^6	R_{SR}	λ_{SO} x 10^6	R_{SO}
1*	0	1.0000	0	1.0000
2	100	0.4164	0	1.0000
3	100	0.4164	10	0.9161
4	1000	0.0002	0	1.0000

* Maximum Reliability Attainable - Perfect Switching

References

1. Carhart, R.R. - Rand Corporation (USAF Contract) Res. Mem. RM-1131.

2. Reliability of Military Electronic Equipment - AGREE Report, 4 June 1957. Report by Task Group 1, Appendix B.

3. Price, H. Walter - Reliability of Parallel Electronic Components. IRE Transactions on Reliability and Quality Control, April 1960.

4. Balaban, Harold S. - Some Effects of Redundancy on System Reliability. Proceedings of the Sixth National Symposium on Reliability and Quality Control, January 1960.

Acknowledgement

The authors wish to acknowledge the assistance of Nicholas Geluso of Grumman Aircraft Engineering Corporation for his many helpful suggestions in the preparation of this paper.

GRAPHIC SOLUTION OF RELIABILITY LOGIC EQUATIONS

William E. Marshall
Senior Reliability Engineer
Minneapolis-Honeywell Ordnance Division
Hopkins, Minnesota

17284 abstract

Reliability logic equations can in some instances become extremely complex because of unavoidable duplication, triplication, sequential events, interactions, interdependencies, etc. In these instances, if reliability logic equations are not used, the results of reliability prediction can be deceivingly inaccurate. This paper presents a simple, accurate procedure for graphic solution of reliability logic equations. A 3-phase, solid-state inverter with a failure detecting and switching circuit and a standby-redundant, single-phase inverter is used as an example of how to solve reliability logic equations graphically.

Reliability Logic - Mathematical Relationships.

To examine reliability logic relationships as they are discussed in this paper, consider a system comprised of a single Black Box, "A". Logically, one could say that:

The system would fail
if
Black Box "A" fails (1)

In most systems, the reliability logic expression can be simplified to the above form. There are, however, redundant systems which cannot be thus simplified. Because certain defects in one redundant channel can cause system failure if these defects are accompanied by certain other defects in another redundant channel, in these instances duplication will arise in the reliability logic expression.

Suppose this system had several black boxes and that in its simplist form, the reliability logic expression included Black Box "A" three times. If one were to analyze the effect of Black Box "A" only, upon the system he would generate either reliability logic expression:

The system would fail
if
Black Box "A" fails
AND if
Black Box "A" fails
AND if
Black Box "A" fails (2)

or reliability logic expression:

The system would fail
if
Black Box "A" fails
OR if
Black Box "A" fails
OR if
Black Box "A" fails (3)

At first glance, the above logic statements appear to be rather ridiculously obvious; however, this type of duplication is neither ridiculous nor obvious when it is inter-woven within a complex set of relationships, inter-relationships, interdependencies, and many black boxes. In the simplified reliability logic expression in one project, two functions appear three times each, and six functions appear twice. That particular expression cannot be further simplified; hence, duplication is unavoidable, and must be properly accounted for.

There are two methods for predicting the failure probability when duplication arises. First, one can assume that no duplication exists (i.e., that logic statements (2) and (3) each involve three separate, non-related black boxes) and set up the formula for the failure probability accordingly. Second, one can set up and solve the reliability logic equation to derive the formula for the failure probability. Although the first method is incorrect, it is often used as an approximation.

Mathematically, logic statements (1), (2), and (3) will give 3 different failure probabilities if duplication is disregarded as explained above in the first method. This disregard for duplication can be expressed as follows: Single function A is assumed to be three separate black boxes. For illustration, they can be shown as A_1, A_2, and A_3. Failure of these black boxes is represented thus: A_1', A_2', and A_3'.

$P(A_1')$ = probability of failure of Black Box "A_1"

$P(A_2')$ = probability of failure of Black Box "A_2"

$P(A_3')$ = probability of failure of Black Box "A_3"

If Q = system's probability of failure

then:

computed from logic statement (1)

$$Q = P(A') \tag{4}$$

and:

computed from logic statement (2)

$$Q = P(A_1')\,P(A_2')\,P(A_3') = \left[P(A')\right]^3 \tag{5}$$

and:

computed from logic statement (3)

$$Q = P(A_1') + P(A_2') + P(A_3') - P(A_1')\,P(A_2') -$$
$$P(A_2')\,P(A_3') - P(A_3')\,P(A_1') + P(A_1')\,P(A_2')\,P(A_3')$$

(see reference 1)

$$= 3P(A') - \left[3\,P(A')\right]^2 + \left[P(A')\right]^3 \approx 3P(A') \qquad (6)$$

Although all three logic statements are correct, the failure probabilities computed in the above manner, which disregards duplication of events, are different. In this example, the reason for the differences between equations (4), (5), and (6) and the magnitude of the differences are easily seen; however, in more complex systems, the reasons and magnitudes become obscure.

Logic statements (1), (2), and (3) can be re-analyzed using logic algebra (see reference 2) with the following results:

Based upon logic statement (1)

$$Q = P(A') \qquad (7)$$

Based upon logic statement (2)

$$Q = P(A' \text{ and } A' \text{ and } A') = P(A') \qquad (8)$$

Based upon logic statement (3)

$$Q = P(A' \text{ or } A \text{ or } A') = P(A') \qquad (9)$$

The results of these two approaches can be summarized thus:

LOGIC STATEMENT NUMBER	FAILURE PROBABILITY			
	DISREGARDING DUPLICATION		USING LOGIC EQUATIONS	
	EQUATION NUMBER	VALUE	EQUATION NUMBER	VALUE
1	4	$P(A')$	7	$P(A')$
2	5	$[P(A')]^3$	8	$P(A')$
3	6	$\approx 3P(A')$	9	$P(A')$

The above reliability logic equations are easy to solve. In complex systems, the solution of reliability logic equations is often difficult or at the least, very tedious and painstaking. A simple method is very desirable.

Example

The need for duplication in reliability logic equations, the inaccuracy of disregarding this duplication, and the method of solving reliability logic equations graphically, can be best illustrated by using a particular example.

3-Phase Solid State Inverter.

Consider a 3-phase, solid-state inverter, with a failure detection and switching circuit, and a standby-redundant, single-phase inverter. A block diagram of this system is shown in Figure 1; however, the circuitry is beyond the scope of this paper. This is neither a randomly selected everyday example nor is it a hypothetical or

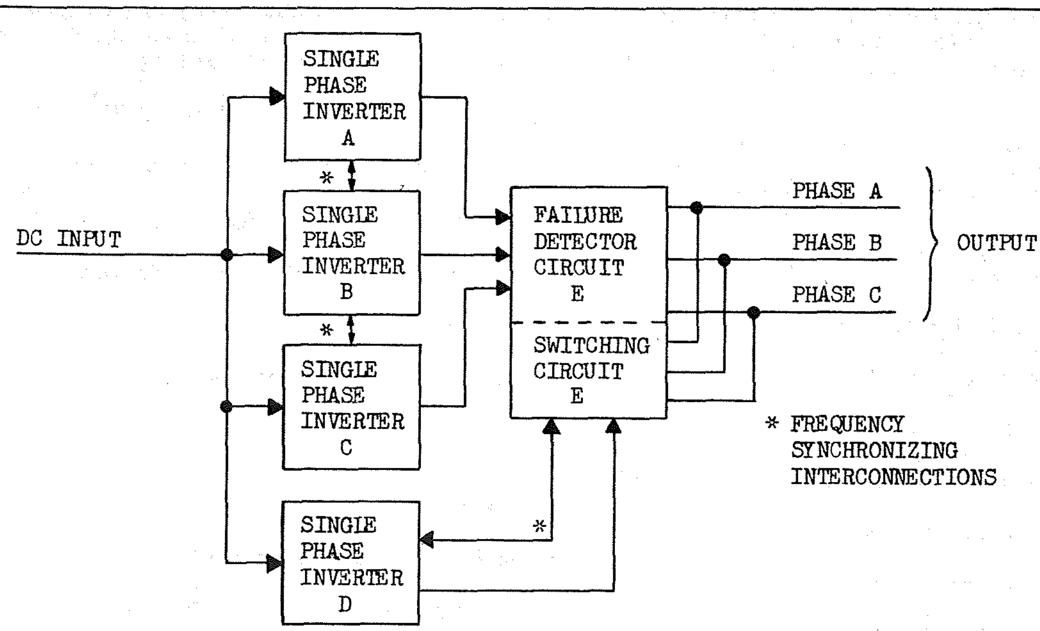


FIGURE 1 - BLOCK DIAGRAM OF 3-PHASE, SOLID-STATE INVERTER WITH ONE REDUNDANT, SINGLE-PHASE INVERTER

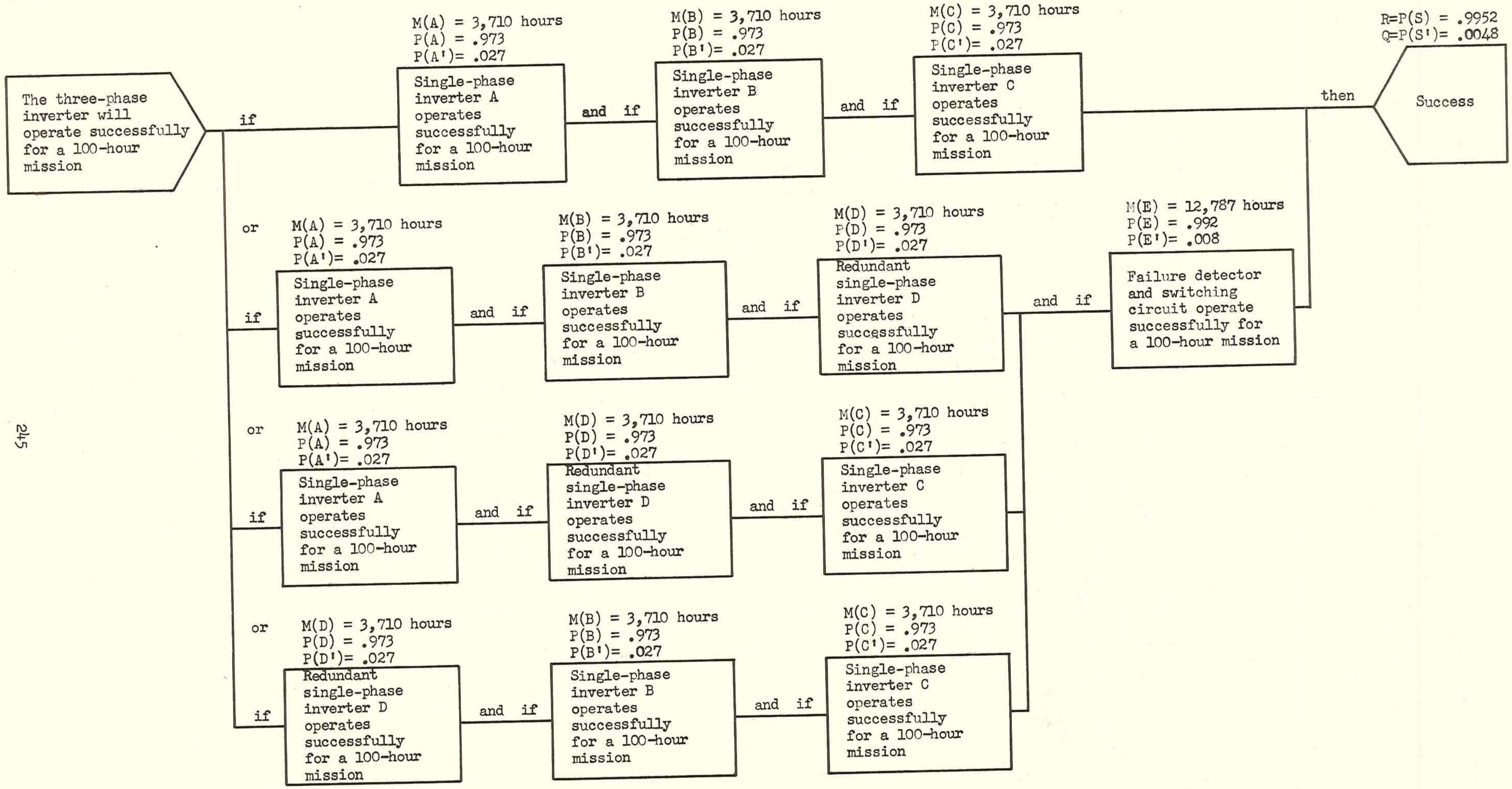
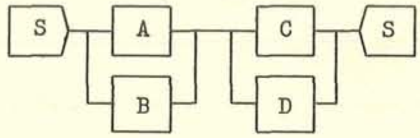


FIGURE 2 - RELIABILITY LOGIC DIAGRAM FOR 3-PHASE, SOLID-STATE INVERTER

ficticous example. An actual system was selected, then modified and simplified so as to best illustrate graphical solution of reliability logic equations. The logic statement for system failure is: the system will fail if one of the primary, single-phase inverters "A", "B", or "C" fail, and if either the failure detector and switching circuit "E" fails or the redundant, single-phase inverter "D" fails, or if more than one of the primary, single-phase inverters fails.

The above logic statement, although correct, is both confusing and inadequate for setting up reliability logic equations; therefore, a complete logic statement in block diagram form is shown in Figure 2. These reliability logic relationships could be correctly diagrammed in many different ways; however, Figure 2 is sufficient for this illustration. This diagramatic technique is discussed further in reference 2. Although the diagram is success-oriented for simplification and ease of illustration, it could have been failure-oriented if desired. Above each block in the diagram, the mean-time-between-failures, the reliability, and the failure probability of the subsystem represented by that block are shown.

Figure 3 shows the basic way in which series - parallel failure probabilities combine to produce system failure probabilities. The failure probability of the combination of Black Box "A" and Black Box "B" logically in parallel is



$$Q = P(A')P(B') + P(C')P(D') - P(A')P(B')P(C')P(D')$$

FIGURE 3 - SERIES-PARALLEL FAILURE PROBABILITY

$$Q_{AB\ PARALLEL} = P(A')\ P(B')$$

and the failure probability of the combination of Black Box "C" and Black Box "D" logically in parallel is

$$Q_{CD\ PARALLEL} = P(C')\ P(D')$$

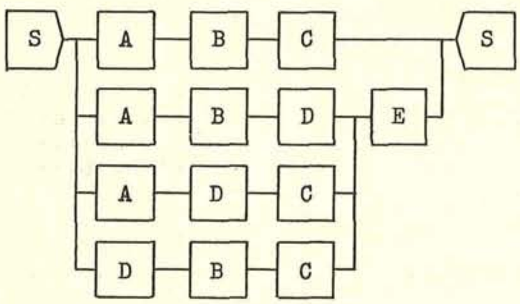
therefore, the failure probability of these two combinations logically in series is

$$Q_{SERIES\ COMBINATIONS} = Q_{AB\ PARALLEL} + Q_{CD\ PARALLEL}$$

$$-Q_{AB\ PARALLEL}\ Q_{CD\ PARALLEL}$$

$$= P(A')P(B') + P(C')P(D') - P(A')P(B')P(C')P(D')$$

$$\approx P(A')P(B') + P(C')P(D')$$



DISREGARDING TRIPLICATION OF EVENTS A', B', C', AND D',

$$Q \approx \Big(P(A') + P(B') + P(C')\Big)\Big(\big[P(A') + P(B') + P(D')\big]\big[P(A') + P(D') + P(C')\big]\big[P(D') + P(B') + P(C')\big] + P(E')\Big)$$

$$\approx .00069$$

USING LOGIC EQUATIONS WHICH TAKE INTO ACCOUNT TRIPLICATION:

$$Q = P\Big[(A' \text{ or } B' \text{ or } C') \text{ and } \big((A' \text{ or } B' \text{ or } D') \text{ and } (A' \text{ or } D' \text{ or } C') \text{ and } (D' \text{ or } B' \text{ or } C')\big) \text{ or } E'\Big]$$

$= .0048$ by graphic solution (See Figure 5)

FIGURE 4 - INVERTER FAILURE PROBABILITY

Omitting the higher order term,

$- P(A') P(B') P(C') P(D')$

will not inject error of serious consequences; hence,

$Q \approx P(A') P(B') + P(C') P(D')$

Higher order terms of this type are intentionally omitted from the calculations in Figure 4.

The above principles for combining probabilities are used to analyze the 3-phase, solid-state inverter as shown in Figure 4. It will be noted that events A, B, C, and D each are shown three times in this diagram (as well as in Figure 2.) The calculations shown in Figure 4 assume that each box in the figure is totally non-related, and by this method it appears that the failure probability is .00069 instead of its true .0048 (to be discussed later.)

Figure 4 also **shows** the following logic equation for the system failure probability:

$$Q = P\Big[(A' \text{ or } B' \text{ or } C') \text{ and } \Big|(A' \text{ or } B' \text{ or } D') \text{ and } (A' \text{ or } D' \text{ or } C') \text{ and } (D' \text{ or } B' \text{ or } C')\Big| \text{ or } E'\Big]$$

Using several sheets of paper and a few hours' time, one can reduce this equation to the exact form:

$$Q = P(A)P(B)P(E)P(C')P(D') + P(A)P(B)P(C')P(E') + P(A)P(C)P(E)P(B')P(D') + P(A)P(C)P(B')P(E') + P(A)P(B')P(C') + P(B)P(C)P(E)P(A')P(D') + P(B)P(C)P(A')P(E') + P(B)P(A')P(C') + P(A')P(B') = .004{,}815$$

or the following approximate form:

$$Q = P(C')P(D') + P(C')P(E') + P(B')P(D') + P(B')P(E') + P(B')P(C') + P(A')P(D') + P(A')P(E') + P(A')P(C') + P(A')P(B') = .005{,}002$$

Where A represents success of Black Box "A" and A' represents failure of Black Box "A".

Graphic Solution. Rather than using several sheets of paper and a few hours time, one can solve this same reliability logic equation in several minutes with one sheet of paper (Figure 5), and a calculator.

Basically, this diagram traces all possible combinations of subsystem performances of a hypothetical population of 1,000,000 inverters.

The first item which the logic in the diagram considers is how single-phase inverter "A" operates. Since .973 is its reliability, single-phase inverter "A" will operate successfully in 973,000 of the original million inverters. This is represented by the number 973,000 above the horizontal line at the right of block: "Event A occurs." Of the 1,000,000 inverters, 27,000 will have single-phase inverters "A" which fail to operate successfully. This is represented by the number 27,000 on the vertical line below the block: "Event A' occurs." Of the 973,000 inverters in which single-phase inverter "A" operates successfully, the next logical step is to examine the performance of single-phase inverters "B" and "C" and if necessary "D" and switching circuit "E". If one traces each individual combination of sub-events in this diagram, he will find that no combination contains a sub-event more than once. This is an especially important check which can and should be made on a complex diagram.

Of the initial 1,000,000 inverters 973,000 will have successful phases "A"; 946,729 will have successful phases "A" and "B"; and 921,167 will have successful phases "A", "B", and "C". Of the original 1,000,000 inverters, 27,000 will have failures in phase "A" and 729 will have failures in phases "A" and "B".

These two combinations illustrate graphical solution of one success logic relationship and one failure logic relationship. Figure 5 shows a total of four success and nine failure logic relationships - each relationship different from all others.

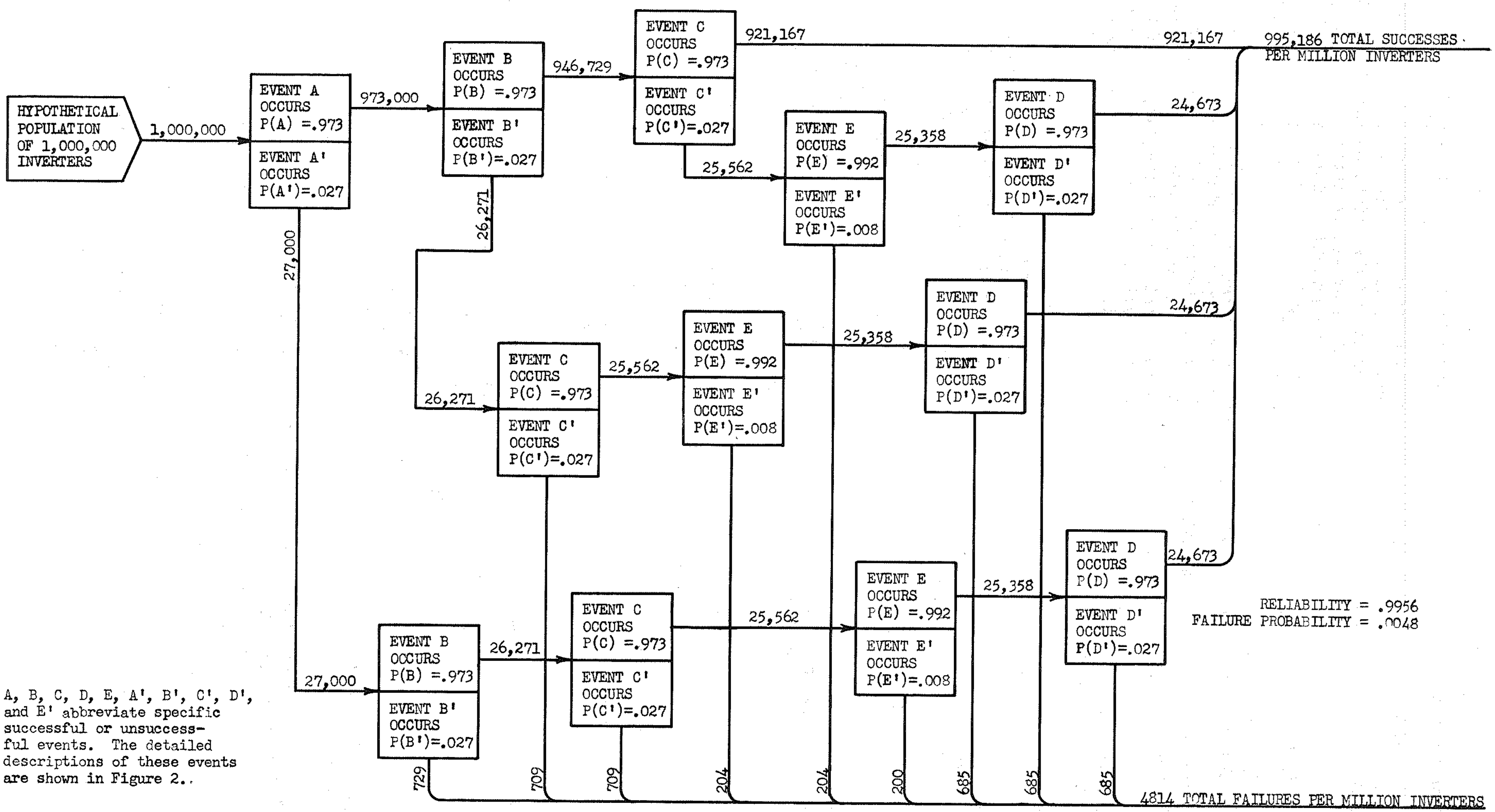
These relationships of subsystem performances which result in system success (listed from top to bottom) are:

A and B and C
A and B and C' and E and D
A and B' and C and E and D
A' and B and C and E and D

and the relationships of subsystem performances which result in system failure (listed from left to right) are:

A' and B'
A and B' and C'
A' and B and C'
A and B' and C and E'
A and B and C' and E'
A' and B and C and E'
A and B' and C and E and D'
A and B and C' and E and D'
A' and B and C and E and D'

Disregarding duplication will not always give falsely optomistic results. In a success-oriented diagram, if duplicate blocks appear logically in series and if this duplication is disregarded, the results will be falsely pessimistic. If duplicate blocks appear logically in parallel, and if this duplication is disregarded, the re-



A, B, C, D, E, A', B', C', D', and E' abbreviate specific successful or unsuccessful events. The detailed descriptions of these events are shown in Figure 2.

FIGURE 5 - GRAPHIC SOLUTION

sults will be falsely optomistic.

It is important to re-emphasize the effect of disregarding the logic relationship approach. In this example, the true failure probability computed by using the logic approach in Figure 5 is .0048; .00069 appears to be the failure probability if logic relationships are disregarded as in Figure 4.

Conclusions

In some instances, reliability logic relationships include unavoidable duplication. If this duplication is disregarded, reliability or failure probability calculations will be in error. This duplication can be properly accounted for by using logic equations. Graphical solution of reliability logic equations is simple, accurate, and time saving.

References:

1. Lindgren, B. W. and Mc Elrath, G.W., Introduction to Probability and Statistics, 1959, pages 17 and 21.

2. Boole, G. An Investigation of the Laws of Thought, Cork, Ireland, 1854.

3. Holtzman, C. Weldon, Jr., and Marshall, William E., "A New Method of Communication Between Engineer and Mathematician Aids System Reliability Prediction", Proceedings of Sixth National Symposium on Reliability and Quality Control in Electronics, Washington, D. C., January 1960, pages 403-408.

MTBF APPORTIONMENT
IN RELIABILITY CONTROL OF THE MAULER DESIGN

Leonard R. Doyon
Raytheon Company
Wayland, Mass.

17285

Summary

One of the more important tasks for the reliability engineer is translating a reliability system specification requirement into subassembly design requirements that have meaning for the design engineer. But the performance of this task alone does not ensure that the reliability design requirements will be met, particularly when the state-of-the-art is being taxed to its limit. The task of translating reliability system requirements into subassembly requirements, called "MTBF Apportionment," must be complemented by firm management reliability policies and effective control procedures.

This paper describes the technique used by reliability engineers in apportioning the MAULER Acquisition and Track/Illuminator radar-subsystems MTBF (mean-time-between-failure) design requirements down four levels to the subassemblies. This paper reveals how the MTBF apportioned values, when made specific design requirements enforced by MAULER Systems management policies and key reliability procedures, evolved into an effective tool for controlling the reliability of the MAULER radar subsystems design presently in its initial R&D phase at Raytheon Company.

For security reasons, certain design features, reliability indices, and the actual breakdown and numerical values in the MTBF apportionment cannot be disclosed.

Introduction

Most reliability specifications and documents in existence today are in agreement that reliability must be designed into an equipment, and that "designing for reliability" must be a part of the earliest concept of system design. The design engineer is told that this is his responsibility, and that he must "design for reliability first, maximum performance second."[1] To assist him in his task, numerous reliability handbooks for design engineers have been published during the past few years. These handbooks contain several hundred pages of "helpful hints," failure-rate tables, derating curves, nomographs and pictographs, stochastic variable concepts and mathematical-probability symbols, Weibull distribution functions, and at least two "improvements" of Tshebysheff's inequality theorem. With all these "useful" tools at his disposal, the design engineer, who is usually responsible for only one or two subassemblies out of the several hundred that make up the complex electronic subsystem or system, is expected to design to meet reliability requirements specified quantitatively in terms of the system MTBF, mission-success probability, or often loosely defined as "...for achieving optimum system reliability." If the reliability requirements are specified quantitatively in terms of MTBF, he is expected somehow to find a way in harmony with the other hundred or more design engineers to meet the single system reliability design objective. Sharing of the reliability design load is not considered since it cannot be even identified much less defined by the design engineers. To say the least, the efforts in terms of meeting the system MTBF requirements are haphazard.

It remains the task of the reliability engineer, disciplined and trained in the terminology and methods of reliability mathematics and engineering, to translate and apportion equitably the system MTBF quantitative contractual requirements into subassembly quantitative requirements meaningful to and within the scope of responsibility of the individual design engineer. Once the reliability design requirements are defined and established for each subassembly by the reliability engineer, meeting the apportioned MTBF requirements for each subassembly, and the contractual MTBF requirement for the system, becomes a team effort by design, system, and reliability engineers.

However, for the MAULER Reliability Program the reliability engineer's task does not end here. In terms of MTBF quantitative values, the reliability contractual requirements for the MAULER radar subsystems, because of the severe environmental conditions expected, represent a need for advancing the radar reliability-design state-of-the-art by a factor of at least two. A very difficult technical enterprise remains. Consequently, throughout the life of the MAULER design program, in addition to providing technical support, the reliability engineer must continually monitor the reliability progress of the MAULER design. He must do this without usurping the traditional prerogatives of the system and design engineers. This he does through the policies and procedures developed and established mutually for the Program by the MAULER Systems Organization and the Reliability Section.

MTBF Apportionment": What it is and What it Does

Where quantitative reliability indices are specified in a contract, the practice of apportioning MTBF values (or failure-rates) for dividing the load in meeting reliability contractual requirements of electronic systems is not new. It has been implemented extensively by the customer, usually the military agencies, and the prime contractors alike in parcelling out reliability requirements to several contractors or subcontractors.[2] It has been used by subcontractors as a means of controlling within their own internal organization the allocation or division of the reliability design load. In essence, it is literally "cutting up the pie" of reliability contractual requirements when no matter how the pie is cut, the whole must equal the sum of all its pieces.

Of course, the objective of any apportionment is equity. An equitable apportionment is one where the design ease or difficulty in meeting the apportioned MTBF is properly distributed for all the subsystems or units concerned. Conversely, an inequitable apportionment defeats the intended purpose, causing an unbalance among subsystem or unit requirements, resulting in the disproportionate added weight, volume, cost and design time for certain affected subsystems or units.

The methods and degree of scientific approaches used for apportioning MTBFs have ranged widely from complicated but sophisticated weighting techniques[3] to "educated guesses." The methods based on "hunches" or "guesses" are of little interest. For our purposes, the only methods of concern are those in which some degree of scientific approach is used. These methods, all of which are basically measures of the comparative degree of complexity of systems or equipments, can be broadly divided into the three main categories described below:

Apportionments by "Weighting Factors"

This method is found most effective for apportioning the necessary MTBF of a large complex system composed of heterogeneous subsystems such as a radar, a computer, and a missile subsystem. Based on analytical studies, advance knowledge or past experience,[4] the apportionment must be made with reasonable equity involving trade-offs or weighting between subsystems such factors as modes of operation, state-of-the-art, and readiness requirements. Since the MAULER radars (See Figure 1) have the contractual MTBF requirements specified by the prime contractor, this method is not germane to the radars. Consequently, a detailed discussion of this method would be beyond the scope of this paper. The interested reader is advised to consult the reference noted.

Apportionment by "Active-Element-Group"

Of these three categories, the "Active-Element-Group" or "AEG" method has been the most useful and applicable to the MAULER radar design effort at Raytheon, and is the method discussed in detail in subsequent paragraphs. The method is based[5] on an approximate count of tubes and transistors (active-element) in the subsystems and assemblies, assuming a given number and types of supporting passive-elements, and modifying the results with weighting factors extrapolated from known field performance of similar equipments. The usefulness of the "AEG" method is its applicability at the most critical time of the design cycle -- during the early design concepts.

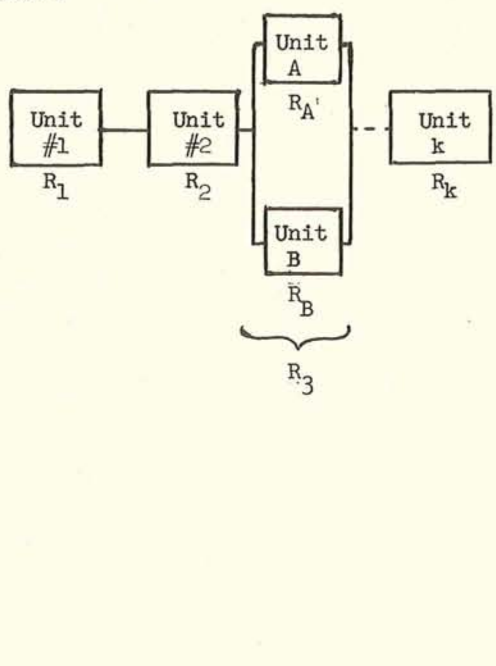
Apportionment by "Parts-Count"

The familiar "parts-count" technique widely used in reliability prediction work was adopted during the latter period of the MAULER engineering model phase, when the component parts list and design parameters were known with a reasonable degree of accuracy, merely to refine the MTBF apportionment made earlier by the "AEG" method.

Apportioning the MTBF for the MAULER Radars

The Reliability Block Diagram and Mathematical Model

The first step in apportioning the MTBF of an electronic equipment subsystem is to analyze the tactical function and modes of operation of the subsystem and of each unit within the subsystem. The next step is to determine for each mode of operation the reliability-dependency of each unit within the system. Any unit whose function and satisfactory operation are vital to the tactical mission of the entire subsystem is considered to be reliability-dependent and is represented simply as one block in a series chain of similarly reliability-dependent units as shown below:



Mathematically, the total reliability R_T of the subsystem, where failures from Unit to Unit are independent, is expressed simply by the well-known formula:

$$R_T = \prod_{i=1}^{n=k} R_i \qquad (1)$$

where, for the example given, R_3 is the reliability of the two redundant units A and B; namely:

$$R_3 = 1 - (1-R_A)(1-R_B) \qquad (2)$$

By assuming that failure occurrences for each unit in the subsystem are exponentially distributed, namely:

$$R = e^{-\lambda t} \text{ or } e^{-t/m} \qquad (3)$$

where λ = failure rate

and m = MTBF

except for the redundant units A and B, the failure rates of all other units are additives:

$$\lambda_T \text{ less } \lambda_3 = \lambda_1 + \lambda_2 + \lambda_4 + \ldots + \lambda_k \qquad (4)$$

Experience has shown that failure occurrences for electronic equipment often exhibit the Weibull failure distribution:

$$R_{(t)} = e^{\frac{-(t-\gamma)^\beta}{\alpha}} \qquad (5)$$

where:

α = scale parameter

β = shape parameter

γ = location parameter

However, for large complex subsystems, the error introduced by assuming $\beta = 1$, giving equation (3) above, is negligible for the purpose of failure rate (or MTBF) apportionment. It is this assumed additive property of failure rates that makes possible simple arithmetic calculations that can be easily explained to design engineers. To make the apportionment task a working tool, simplicity in calculation is more important than unnecessary mathematical precision. In the case of multiple redundant units or assemblies, especially where the units are neither functionally identical nor essential to certain modes of radar operation thus introducing a form of "quasi-redundancy," the MTBF apportionment calculations do not lend themselves to the simple arithmetic techniques such as in the case of series-dependency where exponential failure distribution can be assumed. Fortunately, however, in most practical cases, as illustrated in subsequent paragraphs, the reliability block diagram and mathematical model can be greatly simplified by an engineering analysis of the unit functions and type of circuitry involved.

<u>The Acq Radar Model.</u> For the purposes of this paper, only one principal mode of operation for the Acq radar need be analyzed; namely, the active-search mode, assuming three elevation channels and no computation evaluation as represented by the solid blocks in the reliability model shown in Figure 2. Let us further assume that to satisfy a particular situation, only two out of the three elevation channels need to operate satisfactorily. The reliability mathematical model for the Acq is then properly expressed as:

$$R_T = \prod_{i=1}^{n=6} R_i \left\{ \sum_{X=2}^{B} \binom{3}{X} \left[R_7 \, R_{DC} \right]^X \left[1-R_7 \, R_{DC} \right]^{3-X} \right\} \qquad (6)$$

where the expression in the brackets is the reliability that at least two out of three elevation channels are operating satisfactorily and R_{DC} is the reliability of a Data Converter Unit where:

$$R_{DC} = R_{VC} \; R_{RB} \qquad (7)$$

and R_{VC} and R_{RB} are the reliabilities of the bank of m velocity channels and the bank of n range bins respectively. But,

$$R_{VC} = \sum_{y=k}^{6} \binom{m}{y} R_{vc}^{y} (1 - R_{vc})^{m-y} \qquad (8)$$

where R_{vc} is the reliability of a single velocity channel and k is the number of velocity channels that can fail without causing degradation of the target data. Similarly:

$$R_{RB} = \sum_{z=\ell}^{n} \binom{n}{z} R_{rb}^{z} (1 - R_{rb})^{n-z} \qquad (9)$$

where R_{rb} is the reliability of a single range bin and ℓ is the number of range bins that can fail without causing degradation of target data.

By means of a little reliability engineering analysis of the subassembly functions and type of circuits for velocity channels and range bins, and assuming conservatively that k velocity channels and/or ℓ range bins can fail before causing mission abortion, for a pessimistic estimate that each channel and bin have a failure rate of 25% per 1000 hours, calculations show that for the required mission of the MAULER system:

$$R_{DC} > 0.99999 \qquad (10)$$

Thus, assuming that for the mission R_{DC} is practically unity, equation (6) reduces simply to:

$$R_T = \prod_{i=1}^{n=6} R_i R_7^2 (3 - 2R_7) \tag{11}$$

an equation that can be handled easily for purposes of MTBF apportionment.

The preceding paragraphs have illustrated an earlier statement that with some engineering knowledge of the unit or assembly functions, of the circuits involved, the required mission time, and some appreciation of the approximate failure rates, most reliability mathematical models can be greatly simplified. This is a must for performing MTBF apportionment.

T/I Radar Reliability Model. With the exception of the Cooling Unit which must be shared by both radars, the Track/Illuminator radar units and circuitry are completely independent of the Acq radar (See Figure 3). Except in the Cooling Unit, a malfunction in one radar will not affect the other radar.

The reliability model for the T/I radar is straightforward with the exception of the four Speed Gate-Logic-Coherent Sweep subassemblies which provide some degree of quasi-redundancy. It is not true redundancy in that a single speed gate can be used at any one time for a given target, but each high-and-low-speed gate for an approaching target is complemented by high and low speed gates for receding targets that have passed overhead. One might say that a second chance or shot is thereby provided, but this is not quite correct inasmuch as it may mean getting a second shot after the target has accomplished its mission. Nevertheless, this slight advantage in quasi-redundancy is taken into account for MTBF apportionment purposes.

Measuring the Complexity of Each Unit

By this time, the reader has noted a count of AEG's ("Active-Element-Groups") indicated for each block in the reliability model of Figures 2, and 3. An AEG consists of a tube or transistor, or its equivalent active-element, and its estimated number of related supporting passive-elements. During the early design concepts, the method of assessing the relative complexities of different units or assemblies in a subsystem by estimating the count of AEG's in each unit or assembly, based on whatever engineering information there is on hand or on comparable existing equipment, provides a simple and effective base measure for apportioning or parcelling the subsystem MTBF requirements down to the subassembly level in quantitative terms that are meaningful to the design engineer.

The method of estimating the number of AEGs is not new, having been developed some years ago as noted by an earlier reference. The difference here is that it is not used for prediction purposes. It matters little what the actual failure rates are. We are merely seeking a relative measure of complexity between units and assemblies. For each unit or assembly where a count of AEG has been made or estimated, the MTBF apportioned is simply an inverse porportion of the whole as follows:

$$\frac{\text{Apportioned Unit MTBF}}{\text{Contractural Subsystems MTBF}} = \frac{\text{Total Number of AEGs for Subsystem}}{\text{Number of AEGs for Unit or Assembly}}$$

An apportionment of the failure rate, of course, would be the reciprocal if the assumption of exponential distribution per equation (3) is valid. The only reason for apportioning on the basis of MTBFs rather than failure rates is that the subsystem requirements are specified in terms of MTBFs. For working purposes, we convert all MTBF values into failure rates.

Since the MAULER radars are made up of many types of transistorized analog and digital circuits as well as low-power and high-power active networks, initially it would be very difficult to select and count multiples of a single "typical" AEG as representative of the subsystems. For this reason, three sizes of the most common AEGs were chosen as follows:

AEG_1	AEG_2	AEG_3
1 transistor	1 transistor	1 transistor
3 resistors	5 resistors	8 resistors
2 capacitors	3 capacitors	5 capacitors
1 diode	3 diodes	1 diode
		1 coil
7 parts	12 parts	16 parts

When the three AEG counts were completed, the three types of AEGs were then reduced or normalized to a single "typical" AEG (namely, AEG_1) by considering AEG_2 equal to 1.7 AEG_1, and AEG_3 equal to 2.3 AEG_1, simply on the ratio of number of parts. A moot point may be argued here that normalizing strictly on the basis of parts-count ignores the known fact that transistors, diodes, resistors, capacitors and coils have different failure rates. Had differences in failure rates been considered, a greater accuracy in normalizing would have resulted; but, as proved later by the more accurate parts-count method, no serious inequities in the apportioned MTBF were found where the estimated AEG count was accurate initially.

Special parts, such as waveguide elements and power tubes were assigned weighted "equivalent AEGs." For example, a klystron amplifier, which according to our experience on other projects have exhibited about eight times higher failure rates than for a typical AEG, was counted as "8 equivalent AEGs." Furthermore, 100 radar AEGs ordinarily contain approximately 50 potentiometers, 50 crystals, and 2 pulse transformers.

Wherever this ratio of additional number of parts was estimated to be either too high or too low, proportional weighting was applied to the AEG count. On the whole, there were few instances where this proportional weighting was necessary.

One extreme example of weighting for another reason was the digital computer circuitry. As proved by field experience, digital circuitry is relatively insensitive to parts parameter drift as a result of aging or temperature stress. Digital circuits have field failure rates one-tenth that of analog circuits having an equivalent number of parts. Consequently, the total number of AEGs counted for the computer was divided by ten for the purpose of apportioning the MTBF. Tables 1, 2, and 3 summarize the AEG count, made during the early design concept, and the conventional parts-count was made several months later for prediction purposes and for refining the earlier apportionment. Subsequently, minor adjustments and re-apportionments were made.

Breaking the Unit-apportioned MTBF values to the Assembly (or third) and to the Subassembly (or fourth) levels simply required a repetition of what was done at the Unit level. Apportionments at the third and fourth levels are either incomplete or have to be revised at this date because of recent major changes in the design concept at the subsystem level. Obviously, any major change in the design concept at a given level required an MTBF re-apportionment at all lower levels in order to keep the apportionment equitable.

Meeting the Apportioned MTBF Requirement

Implementing Reliability Control

Once the MTBF requirements have been defined for each subassembly, sound managerial policies must be set into motion and certain key procedures must be enforced to assure that the MTBF requirements will be met. One such procedure or document is the Specific MAULER Engineering Requirements, better known at Raytheon as "SMERs."

The "SMER." As represented pictorially in Figure 4, the MAULER Systems Organization analyzes the customer subsystem requirements, and from these requirements develops and establishes firm design engineering requirements for units, assemblies, and subassemblies via a SMER document. A key design parameter specified in the SMER is the apportioned MTBF value. Thus, the SMER is the vehicle by which the apportioned MTBF value becomes a binding requirement for each subassembly as much as signal-to-noise ratio, power dissipation, peak power, and other radar design parameters to be met and proved. It then becomes the responsibility of the design engineer, consulting with the reliability engineer, to design for meeting the specified subassembly MTBF. The design engineer must make all the failure-rate calculations for his assembly; the reliability engineer checks and verifies the calculations. The design engineer's tool in this task is the MAULER Reliability Engineering Manual.

The MAULER Reliability Engineering Manual. Each design engineer was issued a MAULER Reliability Manual during the early design concept period. The Manual, compiled by the Raytheon Reliability Section at Wayland, contains complete sets of stress-derating curves and failure-rate tables from the RCA TR59-416-1 report and other necessary reliability information extracted from the best key documents originated by reliability engineers at Raytheon and the industry at large. To teach them how to use this tool, periodic reliability seminars and lectures are conducted for the design engineering groups by the Reliability Section.

The Parts Application Review. Daily contact between the reliability and design engineers is maintained through the Parts Application Review Plan (See Figure 4) which is a continuing review of the circuits and parts application by the reliability engineer. In this manner, he is always available for consultation and is able to monitor the progress of the design. As he notices design discrepancies or potential reliability or maintainability deficiencies, he calls them to the attention of the responsible design engineer. Whenever a disagreement occurs on the method of corrective action, or when the action requires an effort or decision that is beyond the control of the interested reliability and design engineers, the reliability engineer initiates a Reliability Corrective Action Request (RCAR) form.

The "RCAR." The Reliability Corrective Action Request or "RCAR" (See Figure 4) is a Raytheon Equipment Division-wide procedure in a one-page format that has proved effective on other projects during the past years in initiating and bringing quick action on reliability problems uncovered by reliability engineers. The initiator, who is the reliability engineer, identifies and describes the problem and recommends a course of corrective action in the upper section of the RCAR form. The addressee, the person responsible for the design of the equipment under question, must give a satisfactory reply within a given number of days. Failure to reply within this period means that the matter will be brought to the attention of management.

Gaining Acceptance by the Design Engineer

Looking back in retrospect some two years ago when the concept of MTBF apportionment was first introduced to the MAULER design engineers, we recall the many stumbling blocks we had to overcome and the many misconceptions we had to clarify to gain the confidence and acceptance of the design engineers. To the highly-analytical mind of many design engineers, the radical idea of treating such intangible entities as MTBFs or failure-rates -- which are in themselves indices of reliability, a probability function -- as if they were neatly-measurable parameters such as resistance, voltage, and frequency, was somewhat

akin to an unscientific, pseudo-engineering, "Ouija-Board" approach. Our seminars and lectures in mathematical probability and statistics to design engineers, if presented at a high-technical level, were often looked upon disdainfully as ostentatious displays of our mathematical prowess; if presented at a lower technical level, the use of visual aids such as playing cards and dice to illustrate the theory of chance in reliability only strengthened their secret suspicions that the reliability engineers used a roulette wheel in apportioning the subsystem MTBF. More effective were our reliability lectures from an engineering approach, particularly on a "work-shop" basis where the design engineers either actively participated or followed an actual reliability analysis and prediction of a given subassembly. But the most effective of all in gaining acceptance has been the daily contacts of our reliability engineers with the design engineers where there was a free interchange of ideas in common engineering language. Thus, the initial barriers of suspicion gradually crumbled.

A significant measure of the acceptance gained is the fact that although management policies and procedures exist for resolution of conflicts that may arise between reliability and design engineers, during a two-year period --- even though the number of conflicts were many --- none was serious enough to submit to managerial arbitration. In our opinion, this is a good record. Of course, due credit for the success must be given to the MAULER Systems Reliability and Quality Control Manager and others in the Systems Organization who from the very onset of the design effort issued management directives in support of the Reliability Section line organization to the effect that the MTBF apportioned values were binding design requirements. This backing dispelled any doubts in the design engineer's mind as to whether the reliability requirements would be enforced.

A Practical Program for a Realizable Goal

During the preliminary phase of the MAULER Acq and T/I radar subsystems design concepts, our initial reliability prediction indicated that:

> If a carefully-planned program for designing reliability into the equipment were implemented effectively, an advancement in radar reliability-design state-of-the-art by an MTBF improvement factor of at least two would be necessary to meet the reliability contractual requirements.

Promoting the state-of-the-art by a factor of at least two represented a technical challenge that never gave us cause for consternation -- we were always confident that although formidable, the technical challenge was not insurmountable, as borne out by later predictions. Of greater concern was the then questionable validity of our premise that a planned control program for designing reliability into the equipment would or could be implemented effectively. The key was the MTBF apportionment. It defined not only the reliability requirements quantitatively for each subassembly, but also parcelled-out the reliability design load to each design engineer. The lock was the SMER or Specific MAULER Engineering Requirements document. It converted the MTBF apportioned values to binding design requirements and thereby validated our initial premise that a reliability design-control program was practical and could actually function if organized properly.

The MTBF Apportionment and the SMER, by themselves, do not guarentee the attainment of our reliability design goal -- they only open the door and make attainment of the goal possible by other reliability engineering tasks. Significant progress towards achieving the goal has been made to date. As we enter the R&D design phase, the R&D model reliability-prediction, which is in process and due to be completed at the end of this month, will measure this progress.

REFERENCES

1. Naresky, J.J. RADC Reliability Notebook, PB161894, RADC-TR-58-111, ASTIA Document No. AD-148868, McGraw-Hill Book Company, New York, N.Y. October 1959, Section 9, p. 6, par. 5.

2. Dertinger, E.F. "A Reliability Program for R&D Projects," Proceedings of the IRE National Convention, The Institute of Radio Engineers, New York, N.Y. March 1957, Part 10, p.39

3. Blanton, H.E. "Reliability-Prediction Technique for Use in Design of Complex Systems," Proceedings of the IRE National Convention, The Institute of Radio Engineers New York, N.Y. March 1957, Part 10, p. 70

4. Reliability Manual, Document No. D2-3246, Aero-Space Division, Boeing Airplane Co. Seattle, Washington. August 1961, pp. 3.2.1.2 - 3.2.1.3.8

5. Bird, G.T. "On Reliability Prediction in Satellite Systems." Proceedings of the National Aeronautical Electonics Conference, Institute of Radio Engineers, Dayton, Ohio, May 1960, p. 204

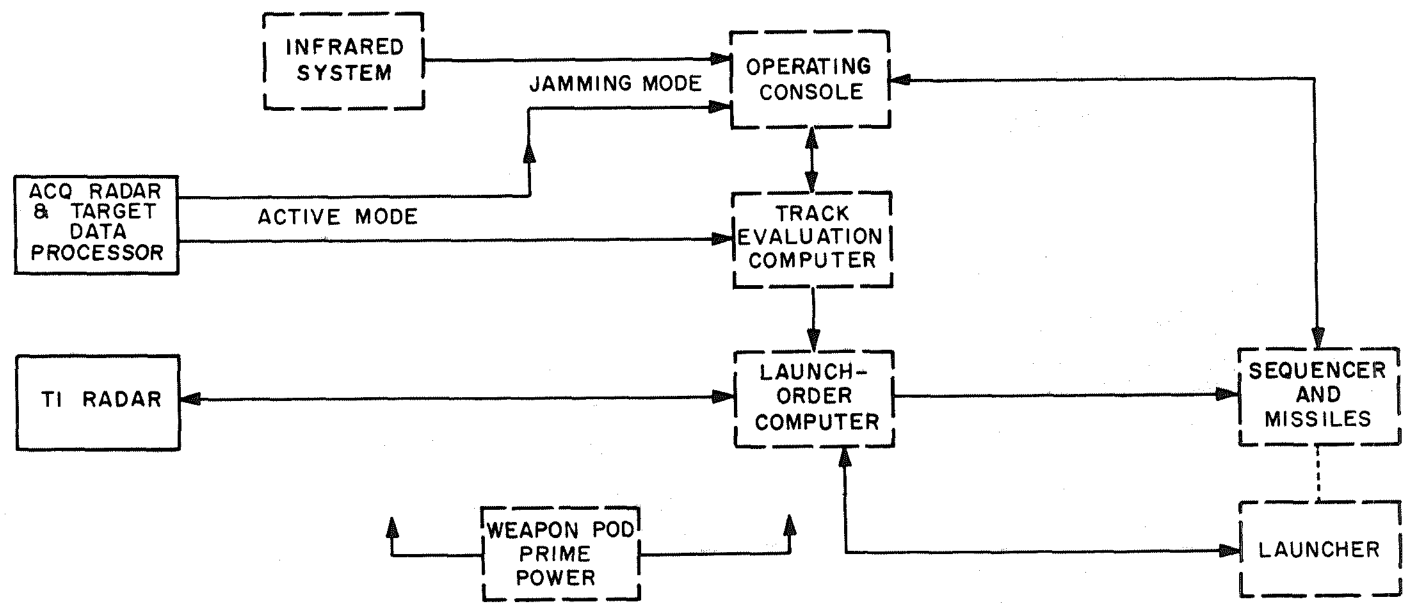


Figure 1. MAULER Weapon System - Simplified Block Diagram

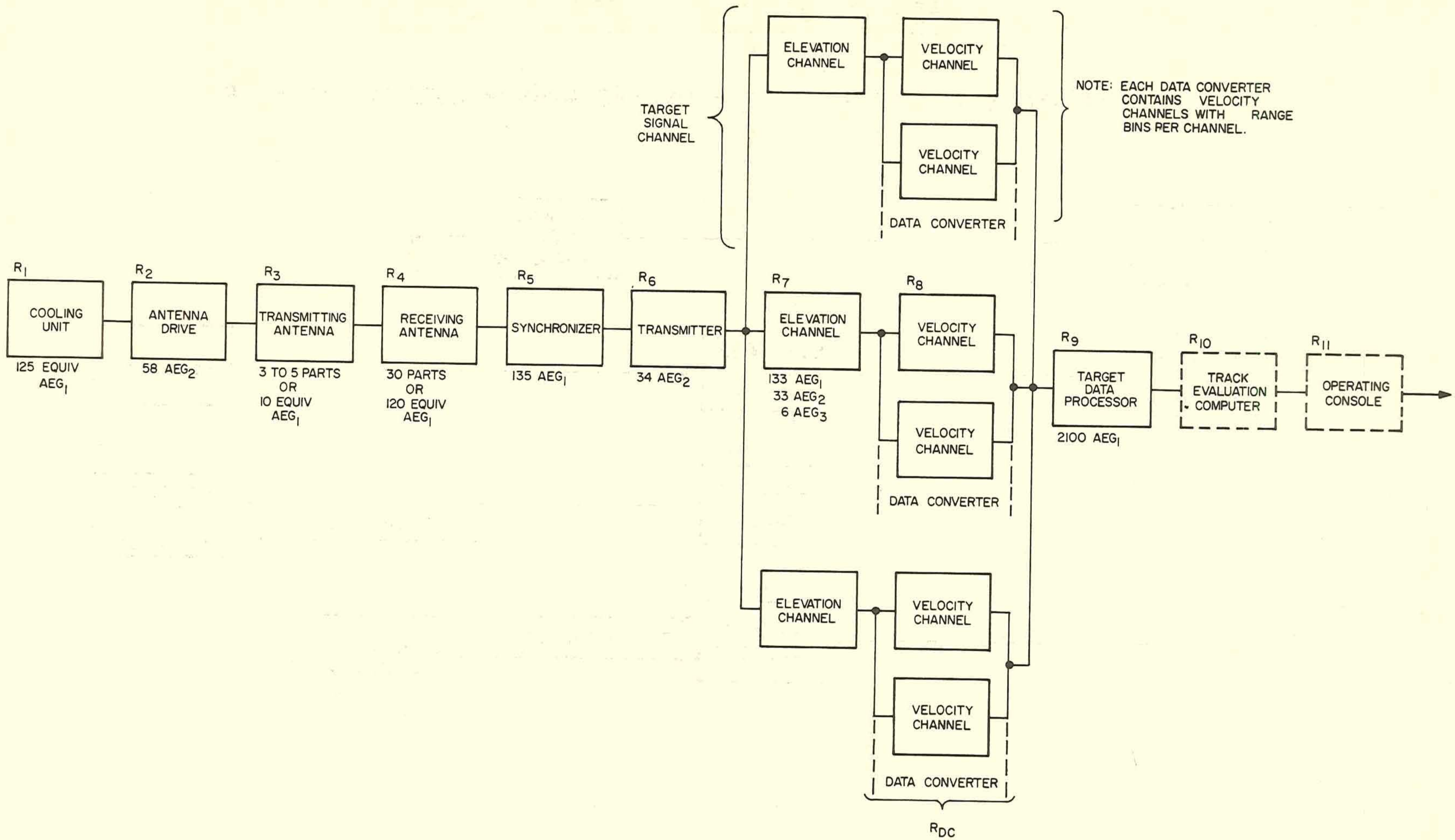


Figure 2. Reliability Model - Active-Search Mode, Acq Radar

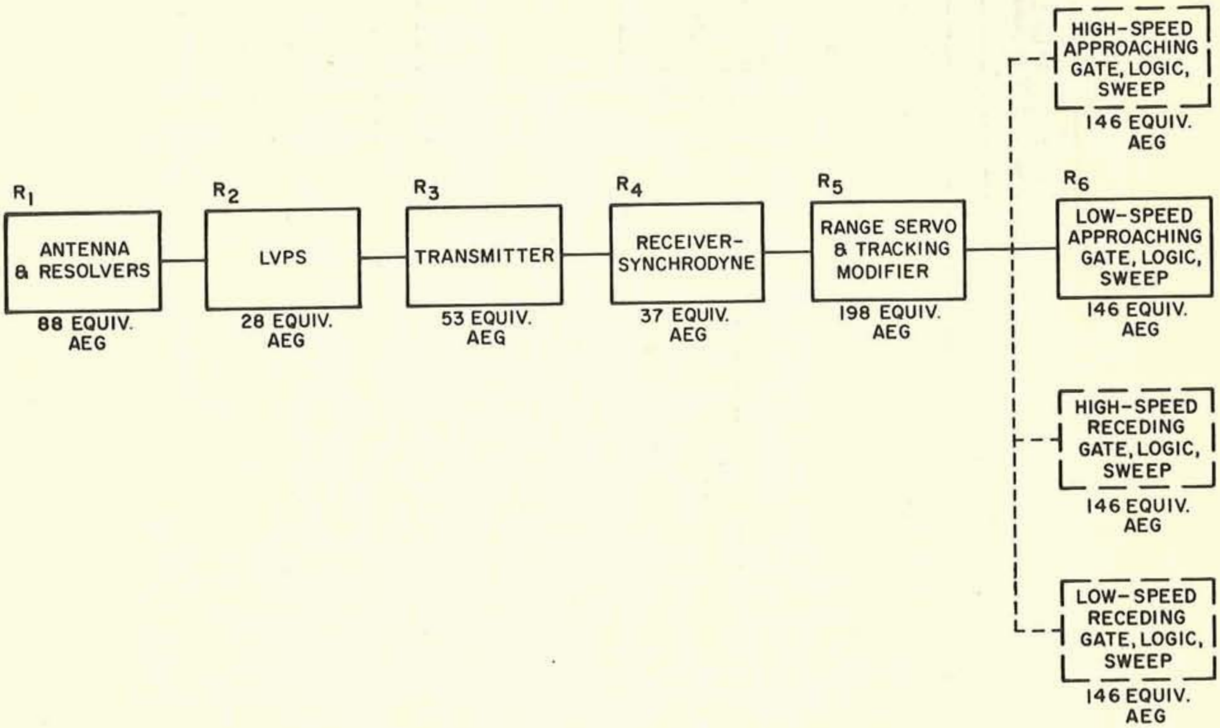


Figure 3 Reliability Model - TI Radar

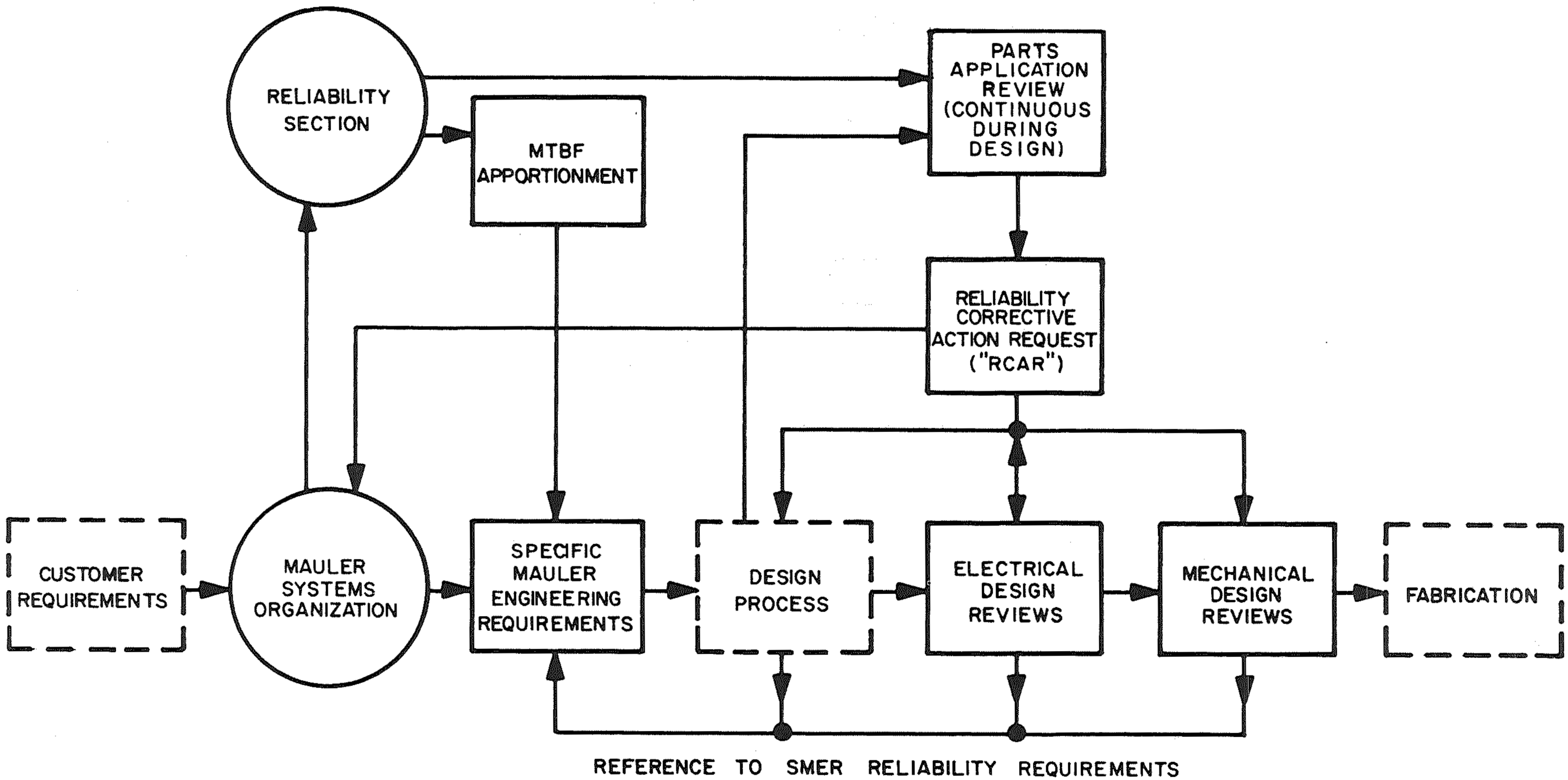


Figure 4 MAULER R & D Management Structure and Key Procedures for Reliability Control of MAULER Design

Table 1. Complexity of Acquisition Radar - Active Search Mode

	Unit	Count of AEG's				Parts Count							
		AEG_1	AEG_2	AEG_3	Equiv. AEG_1	Tubes	Transistors	Diodes	Resistors	Capacitors	Coils, Xfrmr	Misc.	Subtotal of Parts
R_1	Cooling System	-	-	-	125	-	-	-	-	-		50	50
R_2	Ant. Plat. & Drive		58	-	99	-	58	96	317	130	30	19	650
R_3	Transmitter Ant.	-	-	-	10	-	-	-	-	-	-	5	5
R_4	Receiver Ant.	-	-	-	120	-	-	-	12	-	-	51	63
R_5	Synchronizer	135	-	-	135	-	135	62	312	155	5	1	670
R_6	Transmitter	-	34		58	1	33	68	98	116	106	74	496
R_7	Elevation Channel	133	33	6	203	-	166	124	388	193	68	-	939
R_8	Data Converter	Not Considered											
R_9	TDP	2100**	-	-	210	-	2100*	9000*	7,300*	2300*	-	65*	20,765*
	Totals				960	1	2492	9350	8,427	2894	209	265	23,638

*Counts of part classifications in the TDP

**AEG_{TDP}

Table 2. Complexity of Acquisition Radar - Jammed Search Mode

Unit	Count of AEG's				Parts Count							
	AEG_1	AEG_2	AEG_3	Equiv. AEG_1	Tubes	Transformers	Diodes	Resistors	Capacitors	Coils, Xfrmr	Misc.	Subtotal of Parts
R_1 Antenna Platform & Drive Unit	-	58	-	99	-	58	96	317	130	30	19	650
R_2 Receiving Antenna	-	-	-	120	-	3	-	12	-	-	48	63
R_3 Receiver First Detector Assembly	128	-	1	129	2	130	124	215	45	15	-	531
R_4 Passive Receiver	-	6	-	10	-	16	23	116	83	15	7	260
R_5 Sampling Circuit	-	8	-	14	-	8	19	41	18	1	-	87
Totals				372	2	215	262	701	276	61	74	1591

Note; Complexity of R_3 and R_4 takes into account the reduction of AEG's and parts count due to redundancy consideration.

Table 3. Complexity of Tracking - Illuminator Radar

Unit	Count of Equiv. AEG's	Parts Count							
		Tubes	Transistors	Diodes	Resistors	Capacitors	Coils, Xfrmr	Misc.	Subtotal of Parts
R_1 Antenna and Resolvers	88	-	55	19	255	133	16	15	493
R_2 LVPS	28	-	28	44	44	12	12	-	140
R_3 Transmitter (Includes Klystron PA and Stamo Osc.)	53	9	8	21	60	27	21	71	217
R_4 Receiver-Synchrodyne	37	2	28	8	129	124	32	27	350
R_5 Range Servo & Tracking Modifier	198	-	91	159	470	170	60	29	979
R_6 Speed Gate, Logic, Coherence Sweep	146	-	120	160	547	229	7	129	1192
Total	550	11	330	411	1505	695	148	271	3371

RELIABILITY EVALUATION AND ENVIRONMENTAL TESTING OF PRINTED-WIRING-BOARD SOLDER JOINTS

Mark L. Hinkle
Light Military Electronics Department
General Electric Company
Utica, New York

17286

Abstract

During the last three to four years, our Reliability and Maintainability Engineering group has conducted a series of reliability tests of solder (tin, lead; 60-40) joints on printed-wiring boards. The following discussion presents only a few highlights of this testing and evaluation.

In particular, the results and conclusions are given from an extensive test configuration that evaluated the effect on solder-joint reliability of some eight different factors. These results have provided us with definitive quantitative solder-joint failure rates upon which can be based availability-cost tradeoffs and preferred printed-wiring-board solder-joint configurations for ultrahigh reliability even with high rates of temperature cycling and temperatures of 100°C.

I Introduction and Background

It is not unusual to have as many as 130,000 solder joints in a single subsystem for which we have provided printed wiring boards. A solder joint failure rate between 0.1 and 0.001 X 10^{-6} per joint operated hours would contribute--on the average--between 26 and 0.26 failures for each such subsystem during a 2000-hour operating life. As electronic component part average failure rates approach this range (0.1 to 0.001 x 10^{-6} failures per operating hour) solder joints alone could well contribute approximately two-thirds of all failures. Therefore, because of the need for high-reliability single-time missions, and also because of availability-cost considerations, solder-joint failure rates between 1 X 10^{-9} and 1 X 10^{-12} failures per hour are a present need.

II Factors Contributing to Failure

Earlier evaluations of the many factors affecting printed-wiring-board solder-joint reliability[1] indicated that, after cooling, the solder joint has a complicated pattern of internal and external stresses. These stresses result from the slightly different coefficients of thermal expansion together with the inability of a practical manufacturing process to differentially adjust and control the temperatures of each material (solder, board, copper runs, eyelet, and component leads) while the solder is solidifying. Subsequent heating and cooling of joints through component heat dissipation should alternately reduce and then re-establish the built-in internal solder-joint stresses. This stress cycling should cause solder-joint fatigue damage and thereby accelerate solder-joint failure.

Other factors contributing to failure are the decrease in strength of tin-lead (60-40) solder at high temperature[2] and after high-temperature aging. The strength of this solder, after 1000 hours at 100°C, is reduced to approximately 10 percent of its initial value. The percent of initial strength versus time is approximately a negative exponential function.

The above considerations led to the successful development of "high-temperature-cycle" and "medium-temperature-cycle" environmental tests* for accelerated environmental evaluation of printed-wiring-board solder-joint reliability.

III Verification that a Temperature Cycling Technique would Accelerate Solder-Joint Failures

A pilot test was run to determine whether solder joint failures could be accelerated by temperature cycling. Ten printed wiring boards of 1/16-inch XXX-P phenolic, each containing sixty one-watt, 10-ohm composition resistors connected in series, to give a population of 1200 solder joints were tested. A high-temperature cycle (from 25°C to about 97°C and return to 25°C every 30 minutes) was accomplished by applying 130 volts to each board for 20 minutes (dissipating 0.47 watts per resistor) and then cooling with a fan during a 10-minute power-off period. A mild vibration was applied during the testing. Ten failures, distributed between 53 and 6091 hours of testing, definitely established that temperature cycling accelerated solder joint failures.

*Other approaches to the problem of accelerated testing were taken. One of these, thermal-shock testing, may be of more than academic interest. It was found that thermal shock tended to increase solder-joint reliability. Details appear in Appendix 3.

IV Extensive Test Design Configuration

Prior evaluations and test results were used as the basis for constructing a test designed to determine and evaluate the effect on printed wiring board solder joints of: (1) type of joint; (2) board material; (3) board thickness; (4) hand touch-up of solder joints; (5) removal and replacement of components; (6) method of repair of failed parts; (7) temperature; (8) vibration. The first four are design and process factors; the fifth and sixth are user reliability considerations, the seventh and eighth affect both design and use. Design choices among the first four factors will be made in the light of the environmental effects revealed by these temperature and vibration tests. Following is a complete list of the levels of the eight factors tested.

1. Joint Types (design configurations, see Figure 1*)
   a. Standard (eyelet only)
   b. Plated through with eyelet
   c. Plated through without eyelet
   d. Molded plated through

2,3. Printed Wiring Board Materials (2) and Board Thickness (3)
   a. XXXP-Phenolic (1/16-inch and 1/8-inch)
   b. Epoxy Glass (1/16-inch)
   c. Diallyl Phthalate (1/16-inch--molded)

4. In-process Manufacturing and Touch-up of Solder Joints
   a. with touch-up
   b. without touch-up

5. Removal and Replacement of Components Before Test
   a. with removal and replacement
   b. without removal and replacement

6. Two Methods of Repair of Failed Joints
   a. with removal of old solder
   b. without removal of old solder

7. Temperature Environments
   a. High temperature cycle
   b. Medium temperature cycle
   c. High temperature aging (100°C)
   d. Room temperature aging (25°C)

8. Vibration During Life Test
   a. with vibration (1 g rms at the end of each 500 hours of life test for 30 minutes, sweeping through the boards resonant frequency in every 3 minutes and 40 seconds)
   b. without vibration

The test design selected was necessarily a very small subset of the $4^2 \times 3 \times 2^5$ - 1539 tests that would have been required for complete factorial representation of the levels of all factors that could have been evaluated. Conclusive results were, however, obtained for all of the factors that were evaluated.

Table I gives the distribution of printed wiring board sample sizes for the factors indicated. Random samples of the board populations were selected for the test conditions. Removal and replacement of components, touch-up of solder joints, and repair of solder joints were performed upon subsamples of the eyelet only, high-temperature-cycle test conditions.

Samples receiving vibration were removed from the temperature environment and vibrated at 25°C and then returned to test. Each printed wiring board used in the tests had 100, one-watt, 10-ohm composition resistors connected in series, giving a population of 200 solder joints for each board indicated in Table I.* The solder-joint temperature environments were generated in the following manner.

A. High Temperature Cycling (Fig. 2) Each board was connected to 160 volts, giving a 0.256 watts/resistor dissipation to heat the solder joints from 25°C to a maximum of 100°C within 20 minutes. A motor cam mechanism then turned off power and turned on a fan to cool to the 25°C within 10 minutes.

B. Medium Temperature Cycling (Fig. 3) The boards were heated from 25°C to 35°C in 25 minutes, by blowing air across two 600-watt heaters. Then 0.65 volts was applied to the boards, dissipating 0.042 watts per resistor, and heating the solder joints to 45°C in 30 minutes. After 2 1/2 hours at 45°C, cool air was blown across the boards returning the solder joints to 25°C in 30 minutes where they remained for three hours.

C. High Temperature Aging. The samples were heated in an over at 100°C.

D. Room Temperature Aging. The ambient temperature was 25°C.

V Results and Conclusions on the Factors Evaluated

The following conclusions were made on the basis of the test results summarized in Tables II and III. Although estimated final cumulative failure rates are given in Table III, for many sample test conditions the hazard rate was not constant across time; in addition, the distribution of failures between the boards in some cases indicated definite board-to-board

*Illustrations appear at end of paper

*Tables appear at end of paper

differences within a sample. The latter effects are discussed in Section VI, and Appendices 1 and 2.

The following are the conclusions reached upon each of the factors evaluated in the test:

1. Joint Types (Table II). The plated through hole, solder joint is the only solder joint configuration that should be used for high reliability for high-temperature environments from 50° to 100°C when temperature cycling effects are present. No preference for any of the three types of plated through configurations evaluated has been shown.

2, 3. Board Material and Thickness (Table II). At temperature cycling to a maximum of 45°C, where availability-cost tradeoffs indicate an eyelet-only construction has a satisfactory reliability, the order of preference for board materials and thickness is:

A. 1/16" epoxy glass: solder joint failure rate approximately 0.05×10^{-6} failures per joint operated hour. Longevity: exceeds 5720 hours

B. 1/8" XXX-P Phenolic (not tested in medium-temperature cycling environment)

C. 1/16" XXX-P Phenolic: solder joint failure rate approximately 2.6×10^{-6} failures per joint operated hours. Longevity: exceeds 1000 hours.

4. In-Process Manufacturing Hand Touch-up of Solder Joints (Table III). Indicated slight improvement on "eyelet-only" solder joint, at high temperature cycling environment. No improvement indicated at medium temperature cycle. Therefore, it was recommended that in-process hand touch-up of solder joint be discontinued as uneconomical; however, this does not preclude process-shutdown and corrective action when the solder joints of a printed wiring board fail to pass inspection.

5. Removal and Replacement of Components Before Test (Table III). Careful removal and replacement of all 100 resistors, by hand soldering, on two 1/16" epoxy glass boards and two 1/16" XXX-P Phenolic boards, all with an "eyelet-only" construction, indicated that reliability during high temperature cycling was not degraded, but improved--if compared with the other 10 boards. The solder (removed and replaced) joint samples also had failure rates approximating those for the touched-up joints on similar boards.

6. Repair of Failed Joints (Table III).

A. After 482 hours of high temperature cycling and a 1560-hour storage delay, the solder joints of the 1/8" and 1/16" XXX-P Phenolic boards were repaired. The solder joints repaired by melting the solder with an induction heating machine and removing all solder before resoldering consistently indicated a failure rate less than the original failure rate of the sample from which they came. This was not true for the solder joints that were resoldered by touch-up of the failed joint without removing the solder.

7. Temperature Environments (Table II). The order of severity of the test environments in accelerating solder joint failures was:

A. High-temperature cycling
B. Medium-temperature cycling
C. High-temperature aging
D. Room-temperature aging

These effects were noted as being a combination of accelerating the time of occurrence of first failures, as well as accelerating the rate of failure rate increase after the incidence of first failures.

8. Vibration During Life Test. By conducting vibration at discrete times after each 500 hours of temperature cycling, and checking the solder joints before the vibration testing, it was established that failures occurred during the vibration testing. These failures are attributed to the combined effects of decreased solder joint strength during temperature cycling, and final detection of the intermittent or open condition after vibration.

VI Comparison of Test Results with Field Operational Data

An indicated solder-joint failure rate of 0.0003×10^{-6} failures per joint operated hour has been obtained from field operational failure data[3] for the Polaris fire control system. One solder joint failure has occurred after over three billion solder-joint operated hours. The maximum local ambient temperature cycled to in this equipment is about 35°C or 10°C below the 45°C of the medium-temperature cycle of the laboratory test. This, in part--if not entirely--explains the different solder joint failure rate of 0.05×10^{-6} failures per hour for 1/16" thick epoxy glass boards with an eyeleted (not plated through) solder joint, in the

laboratory medium-temperature-cycle environment.

The solder-joint failure rate, for approximately the same solder-joint configuration as above (same type of board and joint construction), from field data for the LMED final MIT Polaris Guidance Computer[4] indicates 0.03×10^{-6} failures per joint operated hours. This is for three failures during approximately 100 million solder-joint operated hours. This later failure rate is for a maximum local ambient temperature near the 45°C maximum temperature of the laboratory medium-temperature-cycle testing mentioned above, and indicates the relative severity of the laboratory temperature cycling testing (about twice that of field operation use, i.e. $0.05 \times 10^{-6}/0.03 \times 10^{-6} = 1.7$).

The most likely explanation for this difference is that, for the field-operated equipment, the 45°C represents the local maximum ambient temperature which only a small percentage of solder joints approach, while in the laboratory testing all solder joints were cycled to within about 3°C of the 45°C maximum.

VII Special Methods of Analysis Applied to Some Comparisons

The probability of chance occurrence of the result indicating the preferred type of joint--plated-through construction--is less than 7×10^{-7} even based upon nonparametric run theory (Appendix 1).

Reference to Figures 4A and 5A indicates that for the best standard (eyelet only) solder joints tested all boards failed earlier than 2000 hours, while none of the plated-through joints had failed. Figures 4B and 5B give hazard rates.

The preference for the 1/8" XXX-P Phenolic is based on the high-temperature test results. (See Figures 6B and 7B for the summary of the worst 1/8" sample and compare with Figures 8B and 9B for the 1/16" samples.) For the 1/16" samples, instantaneous hazard rates of 700 and 24×10^{-6} occurred at or before 180 hours, while for the worst 1/8" sample (Figure 6B) the hazard rate does not exceed 20×10^{-6} until between 180 and 282 hours. (The variability in the distribution of failures between boards is well illustrated by Figure 6A and Figure 7A. This variability is not as extreme as that obtained with one of the 1/16" XXX-P Phenolic board samples in the medium-temperature-cycle testing.)

The conclusions on touch-up, removal and replacement, and methods of repair were based upon comparison of the failure rates for each condition as compared with the failure rates for the initial virgin joints for that same sample. This may be illustrated by considering the two methods of repair of solder joints. With reference to Figure 3A, the samples of 32 and 272 joints repaired by first removing all old solder indicated subsequent failure rates of 0 and 12×10^{-6}, both below that for the original virgin joints. This was also true for the other repair method on the 1/16" XXX-P Phenolic boards. However, repair on the 1/8" boards without removing the old solder indicated an increased failure rate when compared to the original joints. The variability in results obtained when the old solder was not removed could be explained by the care taken in resoldering to obtain a complete remelt of the old solder. This is known to be desirable. With the preferred method not only is a complete melt of solder obtained but new solder is used. Therefore, the removal of old solder was preferred.

Since none of the plated-through solder joints had failed after 4000 hours of high temperature cycling, a few of these solder joints were selected for a qualitative microscopic examination to determine if there was any indication of incipient failure. Figure 10 is a 25-power magnification of a section of such a solder joint which had a slight peripheral surface crack in the solder around the eyelet. No evidence of the crack propagating could be detected.

Summary

This paper has described the development of a high-temperature-cycling test which is most severe for reliability testing of solder joints. The results of laboratory medium-temperature-cycling tests have been compared with field test results to indicate quantitatively the severity of this test level. It is not known what the reliability of these plated-through joint types is, even at the high temperature cycle test conditions. But failure rates less than 0.01×10^{-6} per joint operated hour are indicated as feasible even at operating temperatures to 100°C with extreme temperature cycling. How much lower these failure rates will be at maximum operating temperatures of about 45°C is not known at this time and may not be known for a few years.

Acknowledgements

The author wishes to recognize the contribution of a few of the many people who contributed to these investigations:

Mr. G. Henry, General Electric Company, Ordnance Department, Reliability; and Mr. S. Mercurio, General Electric Company, Light Military Electronics Department, Polaris Reliability; for recent

field data corroborating the realism and failure rate levels of the laboratory testing. Messrs. W. Jezowski and D. Yeaton of the Light Military Electronics Department's Advanced Manufacturing Development group and Quality Control group respectively, for cooperation prior to and during testing. Mr. C. J. Cadieux (LMED Manager of Reliability Engineering) and Messrs. H. L. Benjamin and R. Santin, formerly of LMED Reliability Engineering, who initiated the investigation. Mr. Cadieux, who has been instrumental in implementing the results and has encouraged this presentation, deserves particular thanks. Finally, the author wishes to express appreciation to the two persons who performed much of the testing and the fine details involved in the test setup, failure detection, and the recording of detailed solder joint failure logs: Messrs. E. Malis and R. Malmgren.

Appendix 1

Run Theory Probability

Since there were differences between boards within the same sample, and also large differences (particularly in the high-temperature-cycle environment) between samples in the hazard-rate variation across time, nonparametric run theory is a valid method for making comparisons between samples. This method does not depend upon any assumption of failure distribution across time and is sensitive to differences between boards within a sample.

The following probability indicates that there are only seven chances in ten million identical experiments of all twelve boards of one test sample failing earlier than those of another test sample if the samples are of equal reliability[5].

$$\text{Prob}=2\left[\frac{12}{24}\cdot\frac{11}{23}\cdot\frac{10}{22}\cdot\frac{9}{21}\cdot\frac{8}{20}\cdot\frac{7}{19}\cdot\frac{6}{18}\cdot\frac{5}{17}\cdot\frac{4}{16}\cdot\frac{3}{15}\cdot\frac{2}{14}\cdot\frac{1}{13}\right]=7.4\times10^{-7}$$

In general, the probability of a particular number of runs K (number of groups of like elements being adjacent) happening when there are r_1 elements of one kind and r_2 elements of the other kind is[5]:

for K even:

$$P_K = 2\,\frac{\binom{r_1-1}{K/2-1}\binom{r_2-1}{K/2-1}}{\binom{r_1+r_2}{r_1}}$$

for K odd:

$$P_K = \frac{\binom{r_1-1}{\frac{K-1}{2}}\binom{r_2-1}{\frac{K-1}{2}-1}+\binom{r_1-1}{\frac{K-1}{2}-1}\binom{r_2-1}{\frac{K-1}{2}}}{\binom{r_1+r_2}{r_1}}$$

where: $\binom{A}{B}$ means $\frac{A!}{(A-B)!B!}$, or the number of combinations of A objects taken B at a time.

Appendix 2

Failure Histories Versus Time

Originally, it was intended to compare the results of the different test conditions on the basis of the parameters of the usual failure distributions such as the exponential or the Weibull distribution. However, it is now believed that the selection of the most critical fatigue-accelerating environments for solder joints, namely, temperature cycling, changes both the location parameter and shape parameter of a possible Weibull distribution for the early test time, i.e.

$$R(t) = e^{-[\lambda(t-\gamma)]^{\beta}}$$

It was also found, however, that the hazard rates Z(t) in the accelerated high-temperature-cycle environment did not conform to any of the usual distributions. Therefore, the actual hazard rates for each test condition were computed. Figures 4B to 9B are examples of the estimates of the instantaneous Z(t) and cumulative Z(t) computed as follows:

$$Z(t) = \frac{-\frac{dR(t)}{dt}}{R(t)} \cong \frac{-[R(t+\Delta t)-R(t)]}{\Delta t\cdot R(t)}$$

$$\cong \frac{N(t)-N(t+\Delta t)}{\Delta t\cdot N(t)}$$

where: R(t) is the percent surviving at time t,
N(t) is the number surviving at time t.

Appendix 3

Evaluation of Liquid-Nitrogen Thermal-Shock Testing to Locate Potential Failures

Concurrent with an initial pilot test to determine if temperature cycling could be used to obtain accelerated solder joint failures with failure modes that resembled those of field-operation failure, a final evaluation of a liquid-nitrogen thermal-shock testing technique was made. This test method was intended to either detect weak solder joints or to provide a conditioning that would enable early detection during life test of such intrinsically weak joints. The results of this testing are referenced because they indi-

cated an inverse effect on solder-joint reliability of this particular short-term stress testing. However, component part reliability considerations--damage during this thermal shock--precluded using this inverse effect to improve solder joint reliability.

The conclusions are based upon the following test evaluation. A sample of 20 printed wiring boards was selected. These were 1/16" XXX-P Phenolic boards, each containing sixty one-watt, 10-ohm composition resistors connected in series giving a population of 2400 solder joints. A random sample of 10 of the 20 boards was subjected to 12 cycles of thermal shock: from 80°C to 12 seconds in liquid nitrogen. (Prior thermocouple measurements indicated that the solder joints cooled below -185°C within six seconds, while 11 to 12 seconds was required for the board temperature to stabilize below -185°C.) All twenty boards were then subjected to the high-temperature cycle life-test conditions. The results after 6600 hours of life test were:

1. None of the solder joints given 12 cycles of thermal shock failed during thermal shock testing.
2. Only one solder joint of the 1200 thermal-shocked joints failed during subsequent life test.
3. Ten solder joints of the other 1200 solder joints failed.
4. Twenty-four resistors on the thermal-shocked boards failed during life test. No resistors failed on the other boards.

During testing, detailed examination of all the resistors on the test boards indicated there were radial hairline fractures in the body area of some of the resistors on the thermal-shocked boards. These resistors subsequently failed during the life testing.

References

1. "Evaluation of Techniques for Locating Potential Solder Joint Failures on Printed Wiring Boards", General Electric Technical Information Series, R59EML11, by R. Santin, dated April 15, 1959.

2. "Solder", Publication of Federated Metals, Division of American Smelting and Refining Company.

3. "Thirteenth Numerical Reliability Summary Polaris Fire Control Mariner II NWA Tender Shore Support Submarine" prepared by General Electric, Ordnance Department, Reliability Unit, 100 Plastics Ave., Pittsfield, Mass., dated November 9, 1960.

4. "Failure Trends and Corrective Action Report No. 1 Polaris Guidance Mark I" prepared by General Electric, Ordnance Department, Reliability Unit, 100 Plastics Ave., Pittsfield, Mass., dated January 15, 1962.

5. Feller, W., "An Introduction to Probability Theory and Its Application", John Wiley and Sons, Incorporated, 1951, page 57.

Table I. Test Plan

Board Type	Subjected To Vibration	Hand Touch-Up	NUMBER OF BOARDS ON TEST: High Temperature Cycle	Medium Temperature Cycle	High Temperature Aging	Room Temperature Aging
EPOXY GLASS (Standards)	YES	YES	12		12	
		NO		12		
	NO	YES		12		11
		NO	12	12	12	12
ONE-SIXTEENTH INCH XXXP (Standards)	YES	YES	12		12	
		NO		12		
	NO	YES		12		12
		NO	12		12	12
ONE-EIGHTH INCH XXXP (Standards)	YES	YES				
		NO	15			
	NO	YES				
		NO	15			
EPOXY GLASS Plated Through With Eyelet	YES	YES				
		NO	15			
	NO	YES				
		NO	15	15		
EPOXY GLASS Plated Through Without Eyelet	YES	YES				
		NO	15			
	NO	YES				
		NO	15	15		
MOLDED Plated Through Without Eyelet	YES	YES				
		NO	25			
	NO	YES				
		NO	25			

TABLE II. TEST DATA

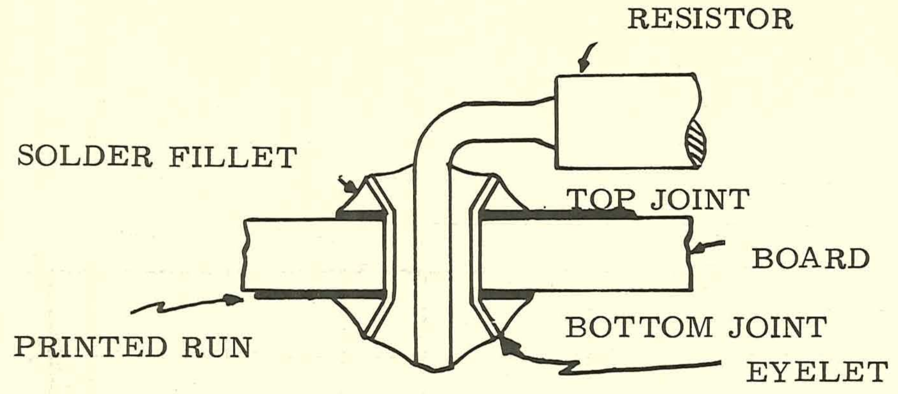
			High Temperature Cycle			Medium Temperature Cycle			High Temperature Aging			Room Temperature Aging		
Board Type	Vibration	Touch-Up	Number of Joints	Hours on Test	Failures*	Number of Joints	Hours on Test	Failures*	Number of Joints	Hours on Test	Failures*	Number of Joints	Hours on Test	Failures*
EPOXY GLASS (Standards)	Yes	Yes	2,400	2,000	1T 258				2,400	2,000	0			
						2,400	5,720	2						
		Yes				2,400	5,720	0				2,200	11,250	0
			2,000	2,000	1T 193	2,400	5,720	0	2,400	2,000	0	2,400	11,250	0
ONE-SIXTEENTH INCH XXXP (Standards)	Yes	Yes	2,400	2,000	221				2,400	2,000	1T 4			
						2,400	5,720	170						
		Yes				2,400	5,720	32				2,400	11,250	0
			2,000	2,000	796				2,400	2,000	0	2,400	11,250	0
ONE-EIGHTH INCH XXXP (Standards)	Yes	Yes												
			3,000	1,500	142T 185									
		Yes												
			3,000	1,500	13T 86									
EPOXY GLASS Plated Through With Eyelet	Yes	Yes												
			3,000	4,000	0									
		Yes												
			3,000	4,000	0	3,000	5,720	0						
EPOXY GLASS Plated Through Without Eyelet	Yes	Yes												
			3,000	4,000	0									
		Yes												
			3,000	4,000	0	3,000	5,720	0						
MOLDED Plated Through Without Eyelet	Yes	Yes												
			5,000	4,000	0									
		Yes												
			5,000	4,000	0									

*Top-joint failures are designated by a T following the number; all others are bottom-joint failures.

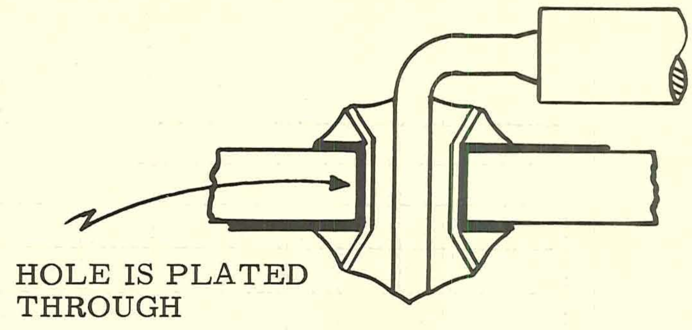
TABLE III. FAILURE RATES OF HIGH AND MEDIUM TEMPERATURE CYCLES

HIGH TEMPERATURE CYCLE																				
			Virgin Joints						Repaired Joints						Touched-Up Joints			Removed and Replaced Joints		
Board Type	Vibration	Touch-Up	Number of Joints		Failures		Failure Rate		Number of Joints		Failures		Failure Rate		Number of Joints	Failures	Failure Rate	Number of Joints	Failures	Failure Rate
			Top	Bott	Top	Bott	Top	Bott	Top	Bott	Top	Bott	Top	Bott	Bott	Bott	Bott	Bott	Bott	Bott
EPOXY GLASS (Standards)	Yes	Yes	2,400	2,400	1	258	0.21	54	--	--					52	4	38	--		
		Yes																		
			2,000	2,000	1	193	0.25	48	--	--				--				400	16	20
ONE-SIXTEENTH INCH XXXP (Standards)	Yes	Yes	2,400	2,400	0	221	0		--	32* 32†	--	0 0	--	0 0	81	3	18			
		Yes																		
				2,000	0	796	0	193		272* 273	--	5 31		12 76				400	14	17
ONE-EIGHTH INCH XXXP (Standards)	Yes	Yes																		
			3,000	3,000	142	185	31	41	142	117	32	44	242	376	--			--		
		Yes																		
			3,000	3,000	13	86	2.8	19	13	57	1	17	8	298	--			--		
MEDIUM TEMPERATURE CYCLE																				
EPOXY GLASS (Standards)	Yes	Yes																		
			2,400	2,400	0	2	0	0.15	--	--					--			--		
		Yes	2,400	2,400	0	0	0	0	--	--					38	0	0	--		
			2,400	2,400	0	0	0	0	--	--					--			--		
ONE-SIXTEENTH INCH XXXP (Standards)	Yes	Yes																		
			2,400	2,400	0	170	0	12	--	--					--					
		Yes	2,400	2,400	0	32	0	2.3	--	--					48	1	3.6	--		

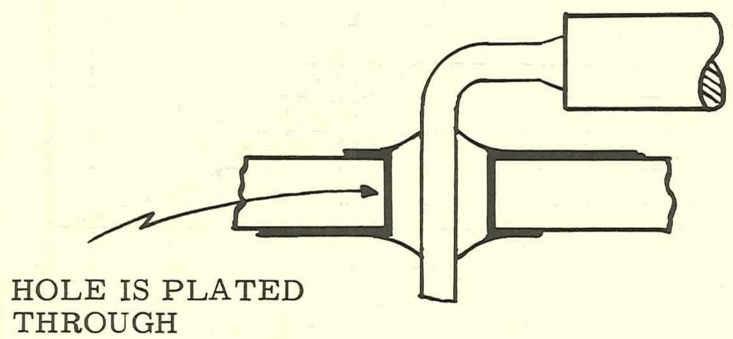
*Repaired by removing all old solder
† Old solder not removed
Failure Rates are in failures per million joint hours of test



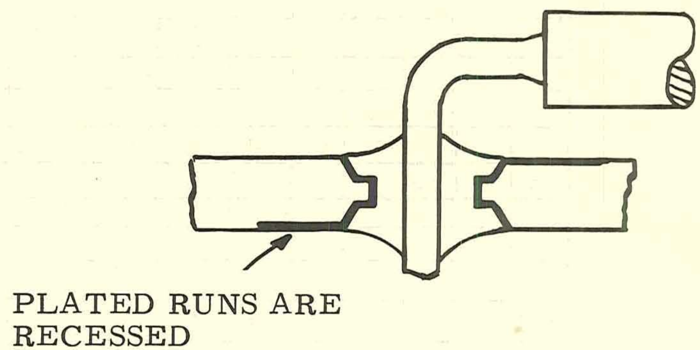
1. STANDARD TYPE



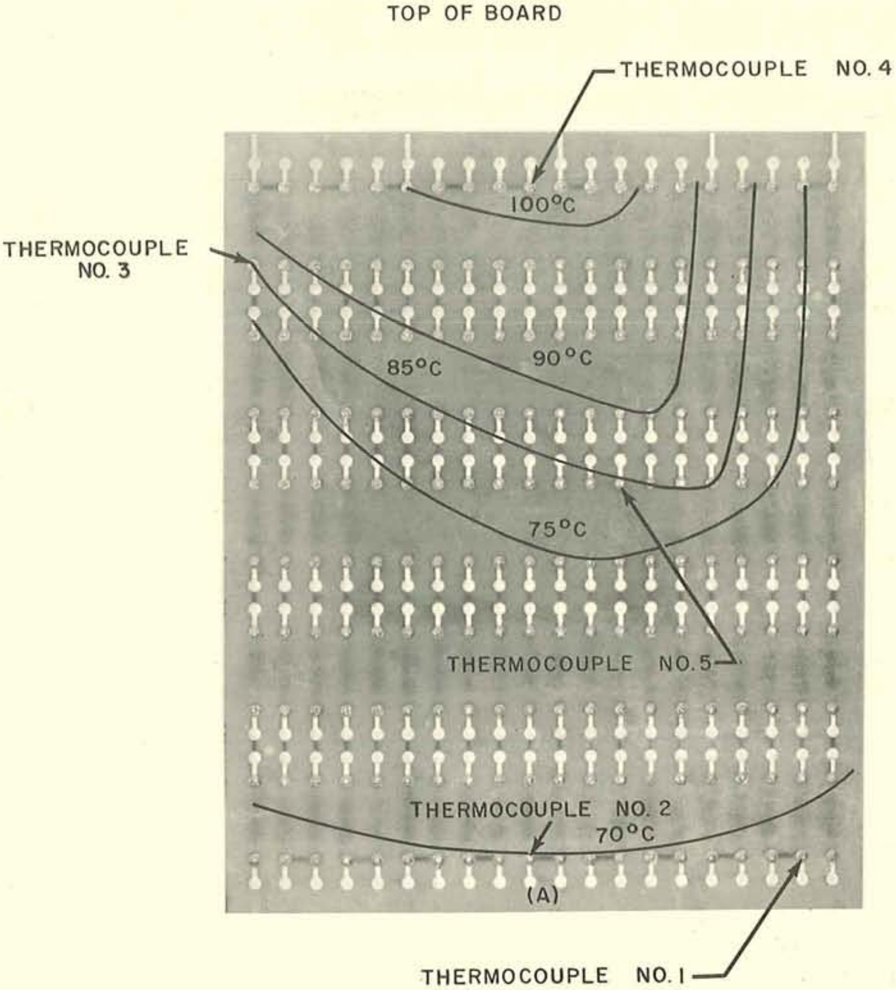
2. PLATED THROUGH WITH EYELET TYPE

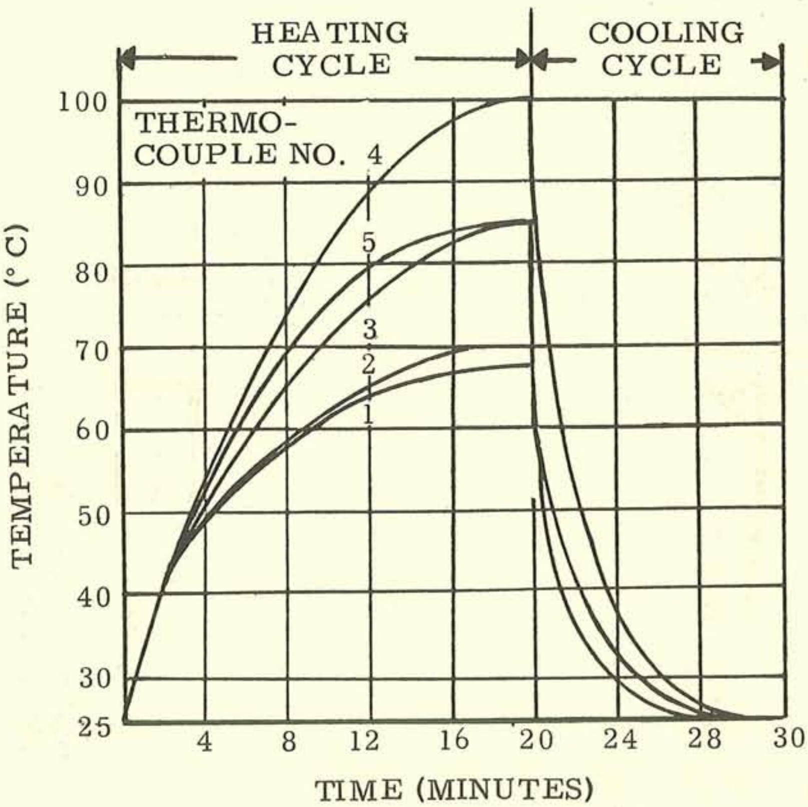


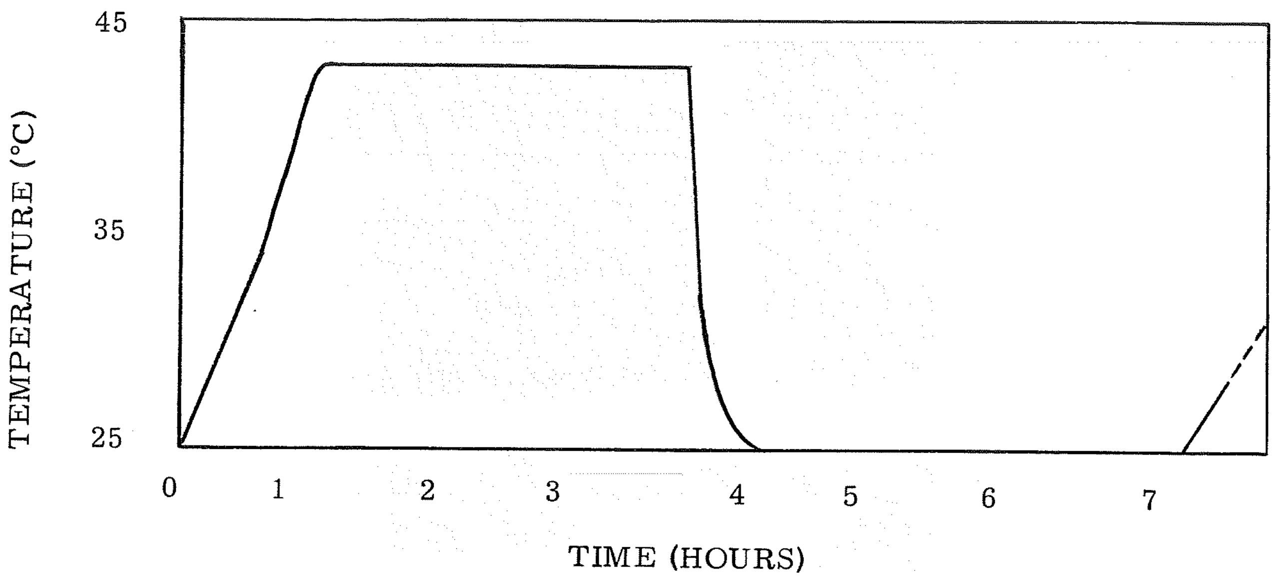
3. PLATED THROUGH WITHOUT EYELET TYPE



4. MOLDED, PLATED THROUGH TYPE


TOP OF BOARD
THERMOCOUPLE NO. 4
THERMOCOUPLE NO. 3
100°C
90°C
85°C
75°C
THERMOCOUPLE NO. 5
THERMOCOUPLE NO. 2
70°C
(A)
THERMOCOUPLE NO. 1

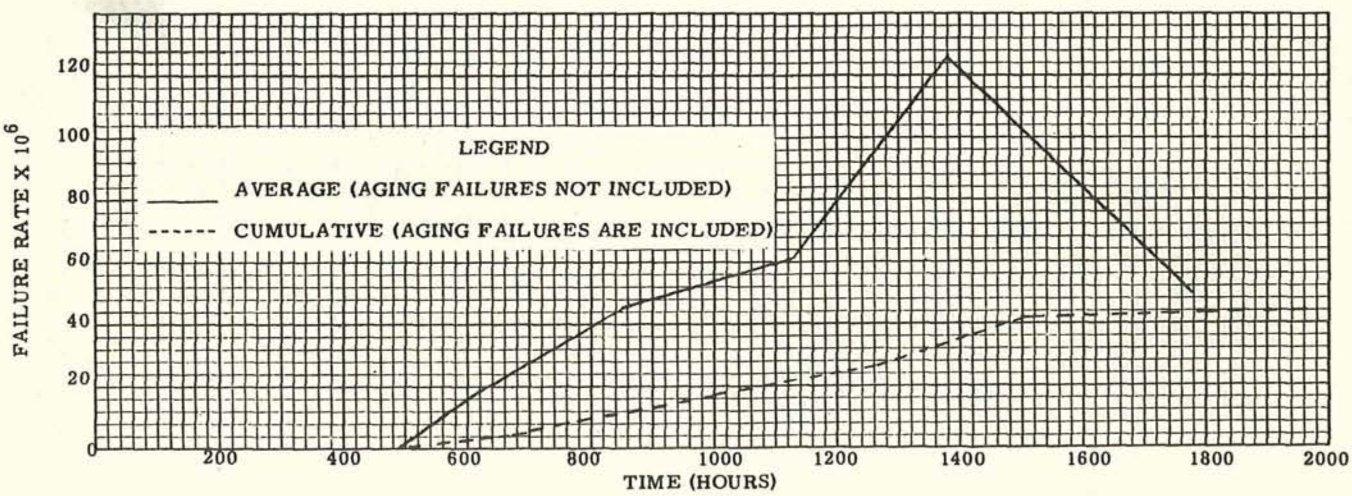

HEATING CYCLE
COOLING CYCLE
THERMO-COUPLE NO. 4
5
3
2
1
TEMPERATURE (°C)
100
90
80
70
60
50
40
30
25
4
8
12
16
20
24
28
30
TIME (MINUTES)


45
35
25
TEMPERATURE (°C)
0
1
2
3
4
5
6
7
TIME (HOURS)

HIGH TEMP. CYCLE		FAILURES PER BOARD											
		Board No.											
Life Test Hours	Total Failures	1	2	3	4	5	6	7	8	9	10	11	12
482													
697	8			1		1	1*	3		1		1	1
1000	39	2		1	5	6	1	8		1	1	7	9
1264	77	2		2	6	11	12	14		1	5	14	12
1500	137	9	2	5	15	23	20	21	1	2	7	24	19
2000	193	12	4	11	23	25	32	25	2	2	10	33	30
		These two boards had all their components removed and replaced. Their failures are not included in totals at left.											

* Top joint

(A)

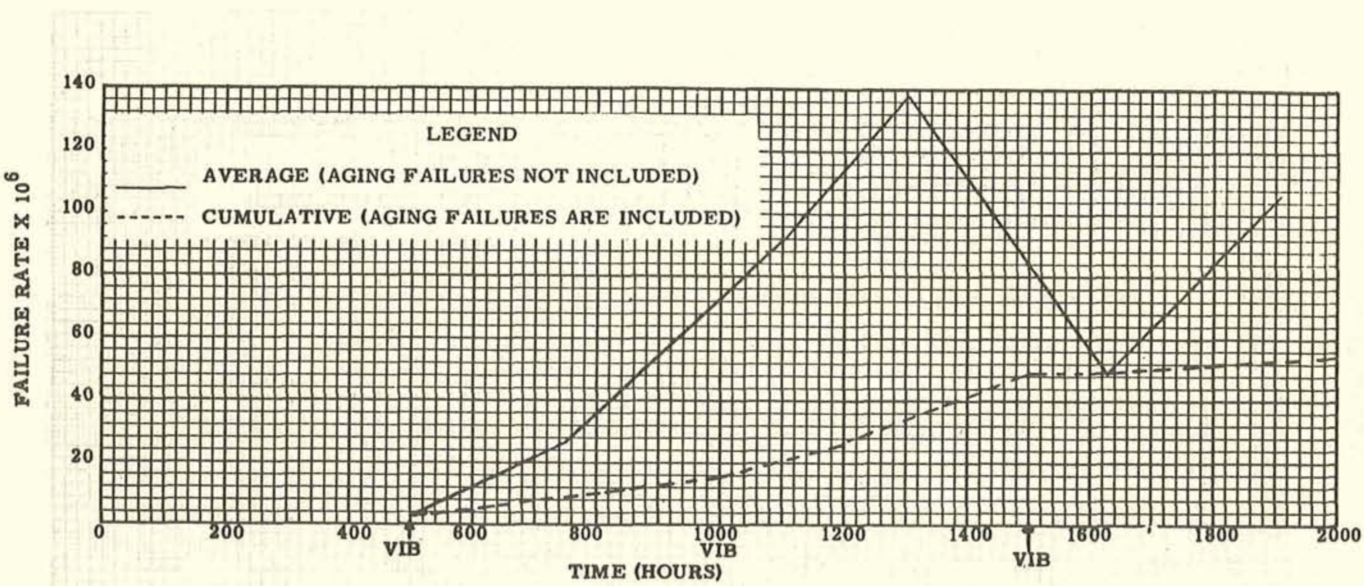


(B)

HIGH TEMP. CYCLE		FAILURE PER BOARD											
Life Test Hours	Total Failures	Board No.											
		1	2	3	4	5	6	7	8	9	10	11	12
500													
VIB I	3		3										
1002	36	5	10		11					10			
VIB II	36	5	10		11					10			
1194	78	7	16	1	20	7	3	3	7	11	2		1
1500	151	12	20	5	27	8	11*	20	18	20	7		3
VIB III	177	14	22	5	29	10	15	20	21	27	9		3
1764	206	16	24	5	34	14	18	28	22	30	10	2	4
2000	258	19	32	6	37	16	23	35	27	39	14	6	5

* One Top Joint Failed

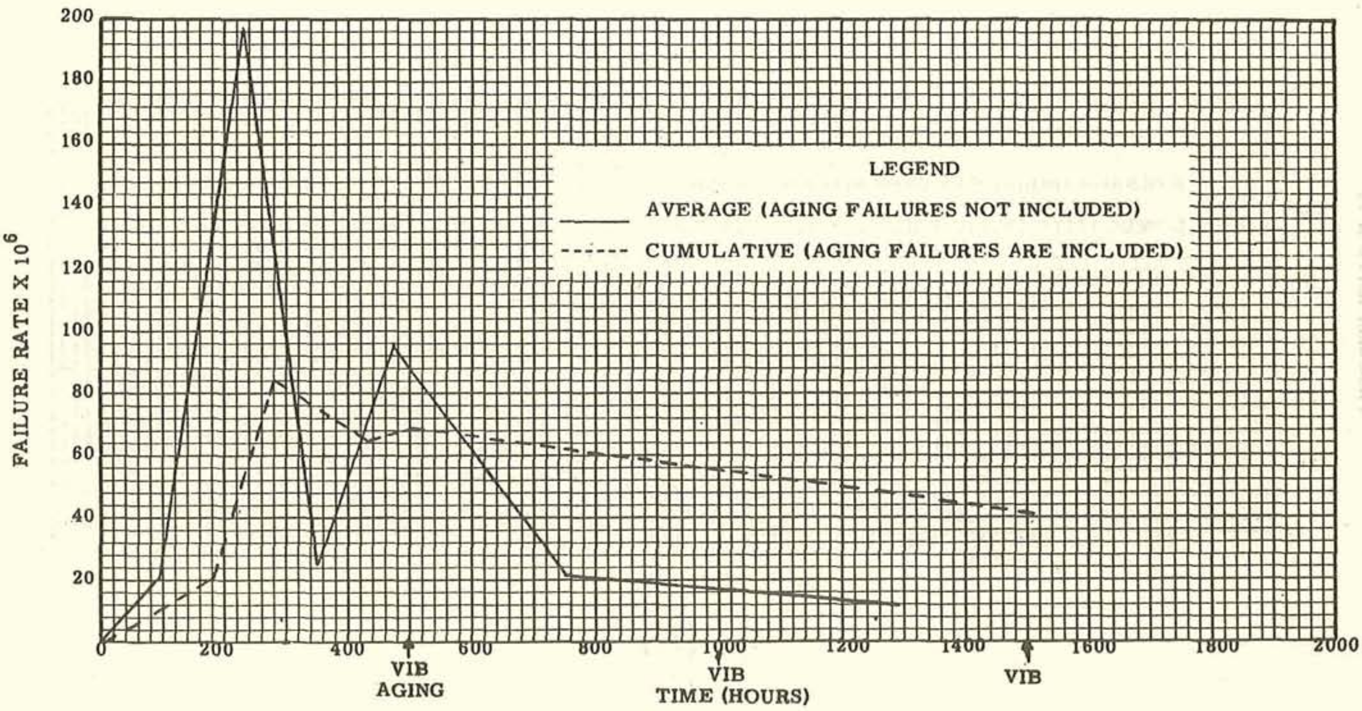
(A)



(B)

HIGH TEMP CYCLE		FAILURES PER BOARD														
		Board No.														
Life Test Hours	Total Failures	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
180	12	3			5				2				2			
282	72	12			20				35				5			
426	83	20			23				35				5			
505	105	23			30				42				10			
1560 AGING	117	24			31				48				13		1	
VIB	135	26			33				50				13		13	
1000	161	32			36			3	57		3		17		13	
VIB	166	34			36	1		3	58		3		17		14	
1500	178	34			39	1		4	61	1	4		20		14	
VIB	185	36		1	41	1		4	61	1	4		20		15	1

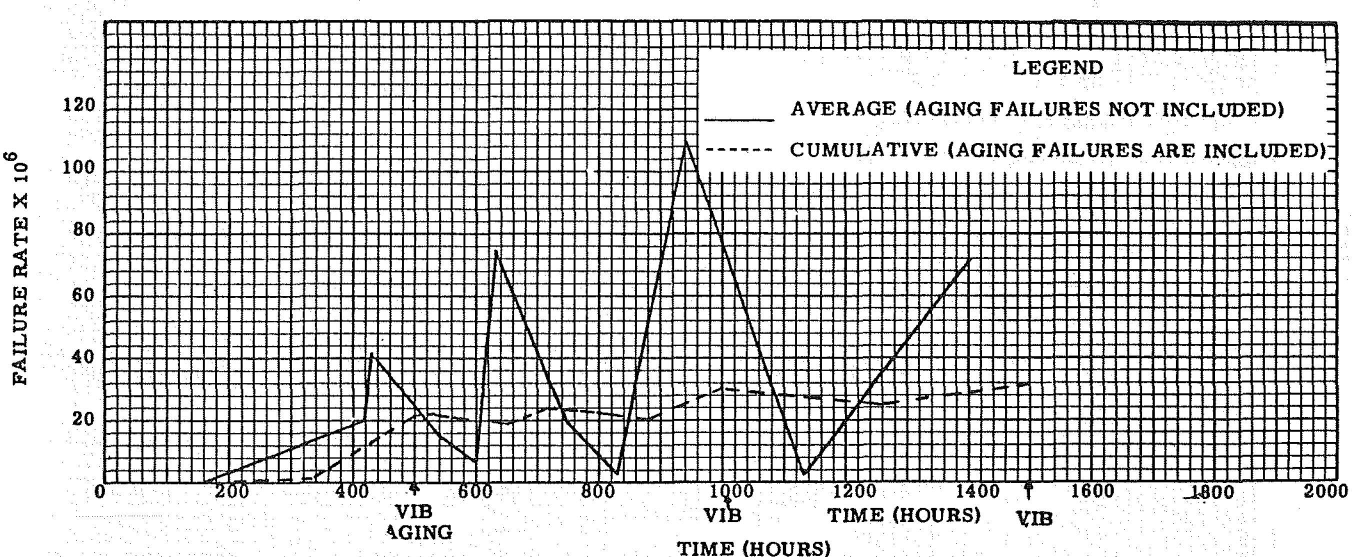
(A)



(B)

HIGH TEMP. CYCLE		FAILURES PER BOARD														
		Board No.														
Life Test Hours	Total Failures	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
330	1				1											
1560 AGING	23				1	14									7	1
505 VIB	33				1	19					1				11	1
529	36				1	19			3		1				11	1
553	37				1	20			3		1				11	1
649	39				1	21			3		1		1		11	1
697	48	1			5	21			7		1		1		11	1
715	52	1			5	21			7		1		2	3	11	1
787	54	1			5	23			7		1		2	3	11	1
883	55	1			5	23			7		1		2	3	12	1
1000	64	1			9	27			7		1		3	3	12	1
VIB	93	7		1	10	31			9		3	1	6	4	17	4
1264	95	8		1	10	31			10		3	1	6	4	17	4
1500	129	8		1	14	34			13		7	1	20	4	21	6
VIB	142	9		1	15	37			13		7	3	23	4	24	6

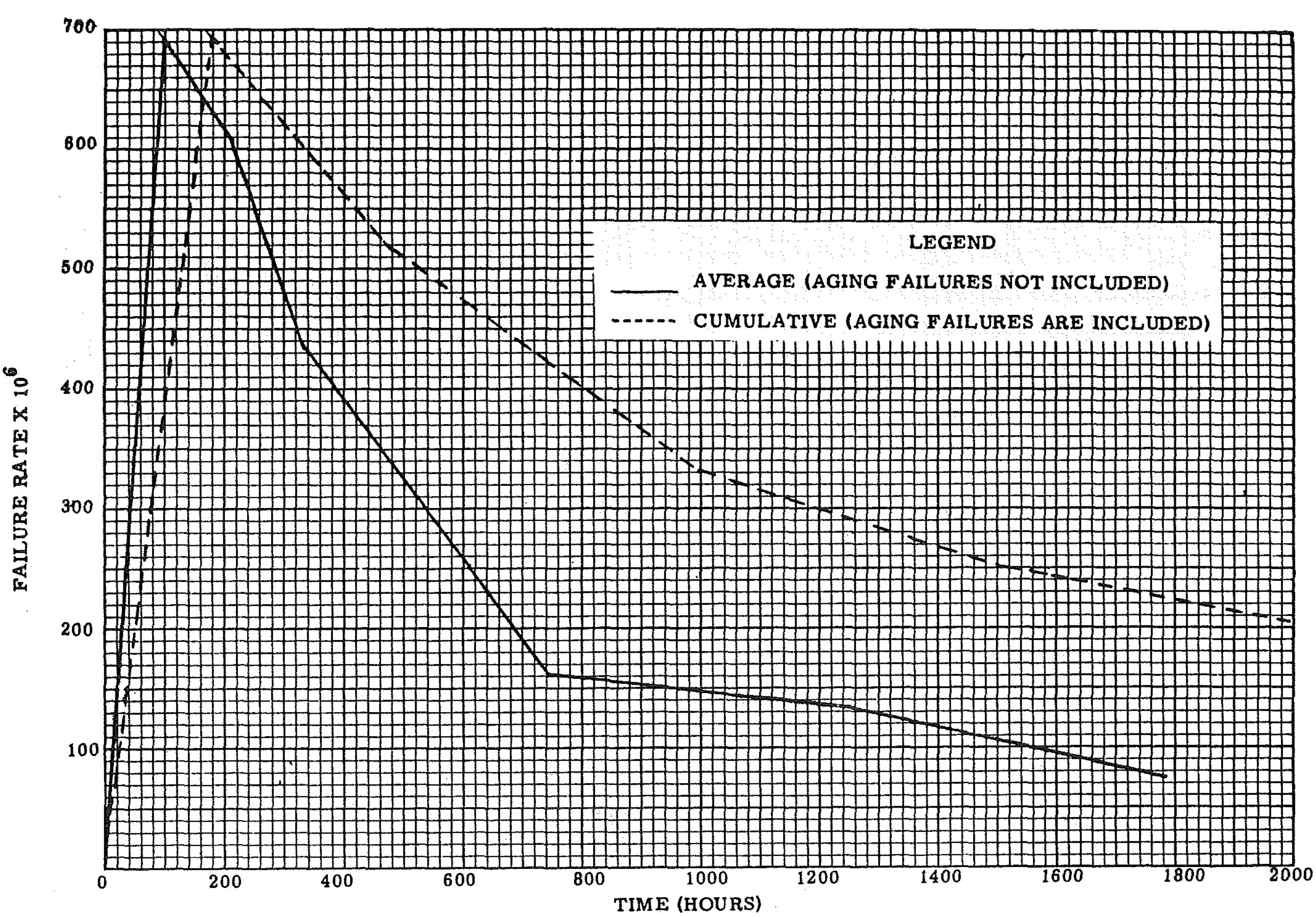
(A)



(B)

HIGH TEMP. CYCLE		FAILURES PER BOARD											
		Board No.											
Life Test Hours	Total Failures	1	2	3	4	5	6	7	8	9	10	11	12
180	253	22		40	53	11	36	63		28			3
260	339	27		72	70	15	46	79		30			3
482	499	40	13	94	95	21	54	88	13	51	30		5
AGING	539	42	13	106	97	25	66	88	13	53	36	5	6
1000	660	53	18	121	112	32	76	119	19	62	48	6	6
1500	748	72	25	137	117	38	87	127	20	72	53	8	6
2000	796	81	28	142	121	42	89	135	21	78	59	8	6
												These two boards had all their components removed and replaced. Their failures are not included in totals at left.	

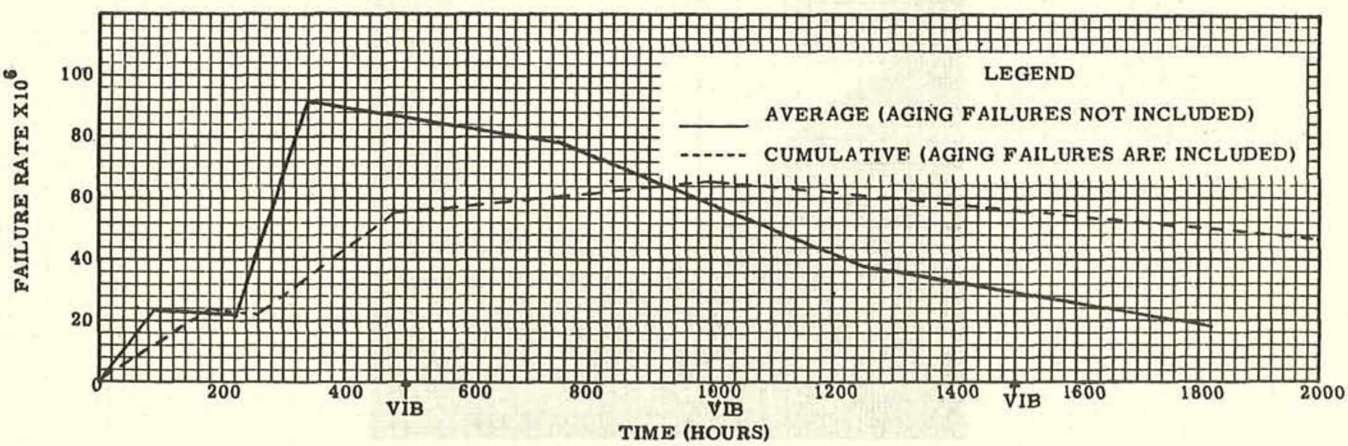
(A)



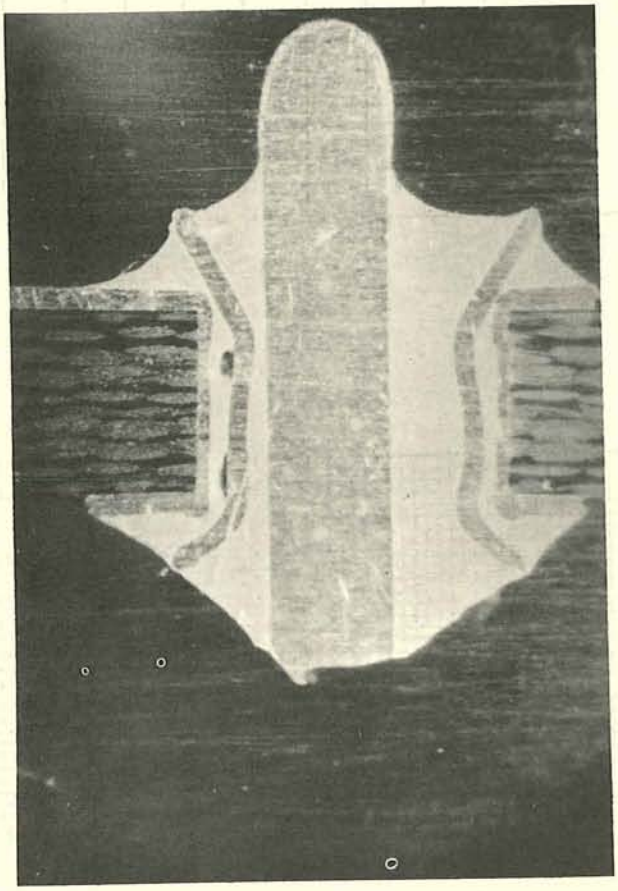
(B)

HIGH TEMP. CYCLE		FAILURES PER BOARD											
Life Test Hours	Total Failures	Board No.											
		1	2	3	4	5	6	7	8	9	10	11	12
180	10										1	9	
260	14										1	11	2
482	62				1					17	6	30	8
1560 AGING	64				3					17	6	30	8
VIB	105	7			5		10		4	24	7	39	9
1000	157	12	1		9	1	19	5	5	26	12	50	17
VIB	178	17	2	1	10	1	24	5	8	26	12	52	20
1500	199	20	2	2	11	2	26	5	8	27	14	58	24
VIB	215	22	3	3	12	3	26	6	8	28	14	63	27
2000	221	22	4	3	14	3	26	6	8	28	15	64	28

(A)



(B)



EXPERIMENTAL EVALUATION OF PREDICTIONS OF PROBABLE CIRCUIT PERFORMANCE

by

M. A. Young
International Business Machines Corporation
Space Guidance Center
Owego, New York

Introduction

The satisfactory performance of a circuit is usually specified in terms of a range of acceptance values for one or more output parameters, such as voltage level, load current, or frequency response. Circuit malfunction occurs if a parameter value falls outside these failure limits. Such a parameter value may be due to a catastrophic failure of a component part or to degradation of component part parameters with age.

Consider, now, the matter of predicting the reliability of circuits during the design phase of a development program. Reliability engineers have concentrated their attention mainly on predicting reliability based on catastrophic component part failure. At the same time, there has been an awareness of the circuit degradation question, and considerable literature now exists on the theory of predicting probable circuit performance.[1,2,3,4] More difficult to find are published experimental results showing the practicality of these techniques.

Predictions of probable circuit performance appeal to those factors in a circuit design which are of direct concern to the designer. These predictions take into account the particular design configuration and the interaction of part parameters on operating points, plus the effects of part parameter drift and their joint probabilities of occurance.

This paper reports the results[7] obtained when six digital computer switching circuits were analyzed for probable performance at 2000 hours life, compared with measured performance at about the same age based on a controlled life test of circuit samples. Three of the more common techniques covered in the literature are applied: the Combination method,* the Monte Carlo method (synthetic sampling), and regression analysis.

* designating the analytical combination-of-distributions for functions of random variables.

Prediction of Probable Circuit Performance

Circuit Failure Characteristics

At some risk of over simplification, it can be said that circuit failures are the result of one of two possible events: (a) catastrophic component part failure, which causes circuit failure in nearly all cases; or (b) component part parameter degradation, which may result in out-of-specification drift of a circuit output parameter even though no part has failed catastrophically. The distinction between these two general types of circuit failure is not always clear in practice. However, catastrophic failure in a component part is usually described as an extreme excursion of a parameter within a short time interval, resulting in severe impairment of the part's normal function. Circuit drift failure may be defined as any crossing of a failure boundry by an output parameter, with all component parts functioning, but with one or more part parameters exceeding initial specification limits.*

Circuit Degradation Failure Model

A performance characteristic of a particular circuit – for example, the steady-state output voltage – is a function of several component part parameters whose exact values for any single circuit are unknown. It will be assumed that a large number of this circuit is to be assembled and operated in identical fashion. The output parameter is treated as a random variable, Y, with continuous distribution function,

$$F_Y(y) = P\left\{Y \leq y\right\}, \tag{1}$$

in which

y is a particular value of the parameter, and

$F_Y(y)$ is the probability that a circuit with parameter value y or less will occur.

* this definition assumes that no combination of acceptable initial parts will be assembled into a circuit having unacceptable output parameters at time zero.

As circuits are operated and begin to "age", the component part parameters undergo changes in value, causing the total population to change in some manner. Therefore, Y_t denotes a random variable defined at some time, "t" hours, and the distribution function becomes,

$$F_{Y_t}(y) = P\left\{Y_t \leq y\right\}. \tag{2}$$

The methods of analysis used in this study require that the drift (or degradation) of individual component part parameters with time be approximately nondecreasing or nonincreasing over the time period of interest. Also excluded are intermittent and catastrophic part parameter failures.

Recalling that satisfactory circuit operation is defined in terms of failure limits on "y", the probability of satisfactory performance of this parameter at time "t", considering only drift, is,

$$P\begin{pmatrix}\text{"y" gives}\\ \text{satisfactory}\\ \text{performance}\\ \text{at "t" hours}\end{pmatrix} = 1 - P\left\{Y_t \leq y_1\right\} - \left[1 - P\left\{Y_t \leq y_2\right\}\right]$$
$$= F_{Y_t}(y_2) - F_{Y_t}(y_1), \tag{3}$$

in which

y_1 is the lower-valued failure limit and

y_2 is the higher-valued failure limit on output parameter "y". *

In this paper, attention is focused upon evaluating how well a predicted distribution function agrees with the observed (measured) distribution of an individual output parameter. The foregoing discussion brings out the fact that predicting distribution functions of circuit output parameters is certainly basic to predicting overall circuit drift reliability. A complete prediction of circuit reliability would utilize these parameter distributions to obtain a total probability of drift failure, which might reasonably be assumed to be an event mutually exclusive from catastrophic circuit failure. Derivation of total drift failure proability must consider whether independence between output parameters exists (it probably does not).

---

* assuming $F_{y_o}(y_2) - F_{y_o}(y_1) = 1$, in agreement with the definition of circuit drift failure stated previously.

Estimating Circuit Distribution Functions

An estimate of the distribution function of a circuit output parameter at various ages may be obtained by fabricating a number of circuits and operating them for the required time, during which the performance of circuits is periodically measured. This method, commonly called a "life test", provides a direct, statistical estimate of the distribution $\widehat{F}_{Y_t}(y)$. However, this method is time consuming and relatively expensive.

Analytical prediction methods are based on the use of test-derived statistical estimates of component part parameter distributions, which are combined to yield a circuit distribution function. A circuit output parameter may be expressed as some function of the part parameter values,

$$y = y\,(x_1, x_2, \ldots, x_i, \ldots, x_n) = y(x_n) \tag{4}$$

in which the "x_i" are assumed to be "n" independent component part parameters, each having a continuous distribution function, at time "t",

$$F_{X_{i,t}}(x_i) = P\left\{X_{i,t} \leq x_i\right\}. \tag{5}$$

Estimates of part parameter distributions are derived from aging tests performed either by the part manufacturer or by the equipment developer, in the early phases of a project. These tests are generally less expensive than circuit life tests, and they may be applicable to many circuits using the same types of component parts. Depending on the application, it may also be possible to estimate $F_{X_{i,t}}(x_i)$ from previous tests of similar component part types.

Deriving $F_{Y_t}(y)$ from the various $F_{X_{i,t}}(x_i)$'s requires that Y_t be analyzed as a joint probability function of all $(X_{i,t})$'s for any "y" value. [5] The general analytical solution in the continuous case proceeds as follows:

a. equation (4) is solved for some x_i, for example x_1, to give the new function,

   $x_1 = h\,(y, x_2, x_3, \ldots, x_n)$;

b. the probability density function of "y", $f_{Y_t}(y) = F'_{Y_t}(y)$

   is then,

$$f_{Y_t}(y) = \int_{x_2}\int_{x_3}\cdots\int_{x_n} \frac{dF_{X_{1,t}}}{dy}\left[h(y, x_2, x_3, \ldots, x_n)\right] dF_{X_{2,t}}(x_2)\; dF_{X_{3,t}}(x_3) \ldots dF_{X_{n,t}}(x_n); \tag{6}$$

the solution of which can be used to obtain $F_{Y_t}(y)$ for any "y". In (6) the notation on integration limits means that they are carried out over all values of the "x_i".

Combination Method

In practice it rarely is feasible to obtain an exact analytical solution due to the difficulty in solving (6), for all but the simplest forms of $y(x_n)$; and then only for restricted forms of $F_{X_{i,t}}(x_i)$'s. For example, if $y(x_n)$ is of the form,

$$y = x_1 \pm x_2 \tag{7}$$

an algebraic solution exists if both X_1 and X_2 are distributed $N: (\mu_X, \sigma_X^2)$, a "Normal" distribution with mean, μ_X, and variance, σ_X^2, given by,

$$F_X'(x) = \frac{1}{\sqrt{2\pi}\;\sigma_X} \exp\left[-\frac{1}{2}\left(\frac{x - \mu_X}{\sigma_X}\right)^2\right] \tag{8}$$

In this special case, $F_Y(y)$ is also $N: (\mu_Y, \sigma_Y^2)$, with parameters given by,

$$\mu_Y = \mu_{X_1} + \mu_{X_2}, \tag{9}$$

$$\sigma_Y = \sqrt{\sigma_{X_1}^2 + \sigma_{X_2}^2} \tag{10}$$

Approximate forms of $F_{Y_t}(y)$ can often be obtained using the combination method by simplification of $y(x_n)$. For example, part parameters with small variance, and those having little effect on "y", may be assumed to be constant for a given "t". The remaining variables must be assumed to be approximately Normal. In some cases, these may be transformed to some new random variable which is approximately Normal. Approximate solutions are given in Reference 5, for product and quotient functions of random variables.

Monte Carlo Solutions

A second method of solution which avoids the difficulties in (6) is the use of synthetic sampling, or the Monte Carlo method. Since all distributions $F_{X_{i,t}}(x_i)$, have been estimated from tests, it is possible to randomly sample values of each $X_{i,t}$ with the prescribed probability that any particular jth variate, $(x_i)j$, will be selected in a large number of trials. A digital computer may be programmed to perform the selections, and provide solutions of $y(x_n)$.[6] It is not necessary (although it is possible) to identify the part parameter distributions as being a specific type, such as Normal, since the computer program samples from a reconstructed form of the observed distribution, regardless of its shape.

Each trial consists of randomly selecting a single complete set of "x_i" values, denoted $(x_n)_j$ for the jth trial. The circuit equation is then solved for this set.

$$y_j = y(x_n)_j . \tag{11}$$

A large number of trials are performed, from which a set of circuit output values are accumulated, $y = (y_1, y_2, \ldots, y_j, \ldots y_M)$. Within this set of values, particular values of "y" occur with approximately the same frequency as would be predicted by an analytical solution of equation (6). This is,

$$F_{Y_t}(y) \approx \frac{(\text{number of solutions, } y_j < y)}{M}, \tag{12}$$

for large M. Note also that complex forms of $y(x_n)$ constitute a lesser problem, since numerical computer solutions are usually feasible.

Circuit Equations

Some choice also exists in deriving a circuit equation, $y = y(x_n)$. A conventional method is to apply linear circuit theory, approximating nonlinear parameter functions where necessary. A second method is to derive an empirical equation using regression analysis, or the "least square" technique, which requires that several circuits be assembled from "tagged" component parts whose parameters have been measured and recorded. Circuit output values are then measured, making it possible to relate an output value, y, to the several (independent) component part parameter values, x_i, by some general expression,

$$y = g_1(x_1) + g_2(x_2) + \ldots + g_i(x_i) + \ldots + g_n(x_n) + \epsilon \tag{13}$$

in which "ϵ" is a particular value of a new random variable, "E", having zero mean. "ϵ" represents an error term not explained

by the regression. Again, in practice it will hopefully be possible to explain most of the variation in "y" using only one or two $g_i(x_i)$ functions, of relatively simple form such as,

$$g_i(x_i) = \alpha_i + \beta_i x_i, \qquad (14)$$

in which α_i and β_i are constants estimated by the least-squares method. Assuming the empirical constants remain valid as circuits age, a prediction of $F_{Y_t}(y)$ can then be made using either the algebraic method or the Monte Carlo method.

Several circuit equations may be required if a circuit operates in more than one distinct "mode". For example, in the switching circuits included in this study, two steady-state conditions were of interest, since satisfactory performance depends on both the UP-level and DOWN-level circuit outputs.

Component Part Parameter Distribution Estimates

Estimates of component part parameter distributions for this study were obtained from life tests during which circuit electrical load and ambient temperature were simulated. Typical test duration was about 2000 hours, and the most common sample size for component parts was about 50. Data reduction followed conventional statistical methods, and an effort was made to establish the type of distribution which best fitted the sample data and at the same time was reasonable in view of physical considerations. Establishing types of distributions and their parameters is primarily of concern to the Combination method of analysis. When the Monte Carlo analysis method is used, it is only necessary to determine several points on the sample frequency histogram, to which the computer program[6] then "fits" an empirical distribution function. In the Combination method, use is made of the first two moments (the mean and the variance) of the sample parameter measurements. These completely describe the distribution, assuming that the population distribution is approximately Normal. If a frequency histogram is skewed noticeably positive, a conversion to a Normal distribution can sometimes be made by a logarithmic transformation.

One of the largest single problems faced in obtaining valid estimates of part parameter distributions for this study was created by the well-known dependence of semiconductor parameters on test measurement conditions, such as temperature and operating point, or "bias". Since it was necessary to use existing part test data, no choice could be exercised in selecting measurement conditions, and the best alternative was to interpolate to the proper operating point. When test measurements were available for more than one operating point, this interpolation was not too risky. Manufacturer's specification sheets were frequently useful, in this connection, since these usually show graphs of "typical" device parameters as a function of operating point, based on accumulated experience. These "typical" curves can be assumed to describe the translation of a part parameter mean value, when dealing with a complete distribution function, which implies that the entire parameter distribution is shifted to the new point. This brings up a final point concerning parameter distribution estimates, related to operating point. The true operating point of any component may be partly determined by the values of other random variables in the circuit, thus violating the assumption of independence between part parameters. If the dependence is strong, it may be necessary to write this relationship into the circuit equation, $y(x_n)$, as was done in several cases in this study.

Results Of Predictions Of Distribution Functions

Description of Study Circuits and Predictions

The circuits employed in the study comprised three active and three passive configurations, varying in complexity from five to nine component parts. The three passive circuits were an OR-gate switching network, and two AND-gate networks of slightly different design. The active circuits were an Emitter-follower, plus a saturating Inverter and a nonsaturating Inverter of different configurations. Each active circuit employed a single transistor of different type.

For each circuit, an equation was derived for two output parameters. These were the steady-state output UP-level and DOWN-level voltages, except for the nonsaturating Inverter, in which case a regression equation was derived for the two transient response terms, Fall Time and Fall Delay Time of the output voltage pulse.

Description of Circuit Tests

The circuit tests, with which predictions are compared, were performed on sample sizes of 24 to 152 circuits, at temperatures simulating the expected application and with fixed electrical loads. These tests were carried out over a period of several years, in connection with three different development programs, with various test objectives, test controls, and measurement techniques. Again, as with the component part tests utilized herein, these tests are not con-

sidered optimum for the purposes of this study.

The question of error sources in measurements was considered, in comparing observed and predicted distribution functions. Estimates were made of the possible bias error in readings, and the sampling error in the mean value of readings which arises from the statistically-small circuit sample sizes. Both of these are illustrated below.

Examples of Results

Figure 1 illustrates a typical result of the cumulative probability polygons (distribution functions) of the observed circuit test results compared with predicted results by two methods – the Combination and the Monte Carlo analyses. In general these two methods yielded similar predicted distributions, especially for the less complex passive circuits. When any appreciable difference existed, the Monte Carlo prediction was usually closer to the observed result. Another general tendancy noted in comparing predicted and observed distributions was that the observations had greater variance. Estimates of the possible reading variance introduced by zero-mean measurement error sources, such as instrument interpolation, parallax, and scale (electrical) errors, showed that the excess variance could have been introduced by these sources.

The possible bias (calibration) error was estimated to be about $\pm 1/2\%$ of the mean voltage level with the test set-up used. This error source could contribute to a general shift of the observed distribution in one direction, for a given set of readings. Since a statistically small sample of each circuit was tested, the representativeness of a sample must be considered in its effect on the mean value of observed readings. The 95% confidence interval about the observed mean helps to indicate the magnitude of the effect this uncertainty causes.

Figure 2 illustrates the greatest difference that resulted between observed and predicted distributions among all circuits, an example which shows the necessity for obtaining component part parameter distributions at the correct operating (bias) point. This particular prediction turned out to be primarily a function of the transistor saturation voltage, measurements of which were taken at "worst case" conditions during part tests. Attempts were made to scale the observed distribution to the proper conditions, but with less than complete success, as can be seen.

Figure 3 shows the best result obtained, which illustrates the sort of correlation which can be obtained between observed and predicted distributions when both the predicted and measured, variables are under good control. In this example, test measurement controls were known to be exceptionally good, and valid part parameter data were available. The difference between the Combination and Monte Carlo predictions in this case is believed to be essentially due to the fact that a more exact circuit equation could be used with Monte Carlo analysis, and that the part parameter distributions were more accurate.

Figure 4 is included to illustrate results obtained using a regression equation, and the Combination method of analysis. The circuit output parameter in this case was Fall Delay Time, a component of the transient response of the circuit. The regression equation used was of the form,

$$T_{DF} = \hat{\alpha} + \hat{\beta}\, W, \qquad (15)$$

in which,

$\hat{\alpha}$ and $\hat{\beta}$ are least-squares constants derived from test measurements, and

$$W = \frac{1}{H_{FE} \; f_{H_{FE}}},$$

the inverse product of the base-collector D. C. gain and the cut-off frequency of this gain parameter for the transistor.

Table I summarizes the over-all results of all predictions, in terms of maximum percentage difference between any predicted distribution and the observed distribution of the parameter from tests. The comparisons are made at the mean value of the observed parameter distribution, and at the approximate plus (or minus) one standard deviation point, whichever was most in error. Twenty out of these twenty-four comparison points show a percentage difference of 5% or less, with a maximum percentage difference of 12% in two instances. The latter result is illustrated in figure 2.

Conclusions And Recommendations

The results of the study show that an analysis of probable circuit performance can produce useful and accurate estimates of the expected distribution of circuit output parameters during operating life, given that valid estimates of component part parameter distributions are employed. Therefore, some of the same objectives as those of a circuit life test may be accomplished, with comparable accuracy, using various analytical

methods. The potential of these techniques for performing a design review during synthesis of design is evident.

The ability to estimate distribution functions of a circuit output parameter by analytical means has been established under life test conditions. Whether or not such estimates can be used to determine the expected drift reliability of circuits under field operating conditions is unknown. However, for certain applications, such as satellite and space missions of long duration, during which environmental stress may approximate constant temperature life test conditions, the analytical results may well furnish the means for estimating drift malfunction probability. Under more complex conditions, the ability of the Monte Carlo method to handle comprehensive circuit equations suggests that, for operational predictions, input, load, failure limits, and temperature may be written into circuit equations and treated as additional functions of random variables with estimated distribution.

The three analysis techniques employed allow certain conclusions to be drawn about relative accuracy, ease of use, etc. It was concluded that each method may enjoy advantages in certain applications. The Monte Carlo method possesses over-all advantages which make it the most attractive for general applications. Outstanding among these advantages are:

- A comprehensive circuit equation may be used, the starting point for which may be conventional circuit equations.
- No practical restrictions exist on the type of circuit equations, the numbers of variables, or the type of distribution functions used.
- Evaluation of several failure sources may be readily performed in a single analysis.
- Reanalysis is simplified, for example, if component part values or distributions are changed.
- Accuracy is generally better.

Disadvantages which may be important in some instances are:

- A medium-to-large capacity computer is required for analysis.
- Computer programing is required, a step which usually means the designer cannot perform the entire analysis himself.

The Combination method proved to be relatively easy to use after circuit equations were simplified. It provided quicker results than the Monte Carlo method and, for the simple passive circuits (AND, OR gates), results were of comparable accuracy in most cases. Where differences were noted, however, the Monte Carlo results were closer to the measured circuit distributions. The disadvantages of the combination method were noted as:

- The required simplification of defining equations may result in noticeable loss of accuracy.
- The method is restricted in both number of variables and type of part parameter distributions which can be handled.

The regression method produced good results for the analysis of two transient terms which contribute to circuit response time. The method appears to have special application when defining equations are not easily obtained from a circuit analysis or when circuit equations cannot be written in terms of the distributed parameters which are commonly measured for component parts. It should not be compared directly with either of the previous methods for these reasons. In the regression applications in this study, analysis gave adequate results when using the Combination method. In more complex applications the use of a Monte Carlo analysis of the regression equation should not be overlooked. Two disadvantages of the method are as follows:

1. fabrication and measurement of a sample of circuit outputs and corresponding part parameters is required to develop the regression relationships;
2. considerable effort may be necessary to determine the important part parameters to include in an analysis and to develop useful relationships with the output parameter.

Experience with the reduction of component part test data to estimate distributions for part parameters indicated that acquisition of good data is a major problem even with large available quantities of data. Test design for component parts was in conformance with the circuit design philosophy, resulting in most test measurements being taken at "worst case" limits for circuit applications. Resultant distribution estimates were not valid in most cases for predictions of circuit life test performance. Attempts to adjust distributions to other conditions were reasonably

successful, judged by over-all results. It should be possible to avoid much of this problem, if probabilistic analyses of circuits are anticipated prior to design of part tests. Approximate distributions, obtained by adjustment for improper measurement conditions, offer an alternative which should be investigated for specific applications.

Acknowledgments

The author expresses appreciation to Messrs. J. E. Anderson, T. L. Burnett, and E. A. Reeve for helpful suggestions in the course of the study on which this paper is based. The study was performed under Contract AF30(602)-2418. Air Research and Development Command, Rome Air Development Center, Griffis Air Force Base, New York, and Advanced Research Projects Agency Order No. 168-61, Washington 25, D. C.

References

1. Hellerman, L. and Racite, M. P., "Reliability Techniques for Electronic Circuit Design", IRE Trans. on Reliability and Quality Control, Vol. 14, pp 9-16; September 1958.

2. Nussbaum, E., Irland, E. A., and Young, C. E., "Statistical Analysis of Logic Circuit Performance in Digital Systems", Proc. IRE, Vol. 49, no. 1, pp 236-244; January 1961.

3. Brown H., Marini, H., and Williams, R., "Evaluation and Prediction of Circuit Performance by Statistical Techniques", ARINC Monograph #5, ARINC Research Corp.; February 1958.

4. Anderson, J. E., "Predicting Drift Reliability of Digital Circuits", Proc. 6th Joint Military-Industry Guided Missile Reliability Symposium, 15-17 February, 1960.

5. Wilkinson, R. I., "The Combination of Probability Curves in Engineering", Trans. Amer. Inst. Elec. Engineers, Vol. 61, pp 953-963; December, 1942.

6. Doxtator, R. H. and Arnold, F., "PRESS: An IBM 704 Program for Performance and Reliability Evaluation by Synthetic Sampling", IBM Technical Report TR01. 01. 112. 602, IBM, Endicott, N. Y.; December 1959.

7. Final Report on Prediction of Circuit Drift Malfunctions of Satellite Systems, ARPA 168-61, Contract AF30(602)-2418, (Unclassified). IBM No.: 61-928-28; November 1961.

Table I

MAXIMUM ERROR IN OUTPUT PREDICTED BY ANY METHOD, AS PERCENTAGE OF OBSERVED VALUE AT THAT POINT

Circuit	At mean value	At plus or minus one sigma point
AND-Gate (#1) UP-level	less than 1%	less than 1%
DOWN-level	less than 1%	3%
AND-Gate (#2) UP-level	less than 1%	less than 1%
DOWN-level	less than 1%	5%
OR-Gate UP-level	less than 1%	less than 1%
DOWN-level	2%	3%
Emitter-Follower UP-level	less than 1%	less than 1%
DOWN-level	4%	9%
Inverter, Saturating UP-level	12%	12%
DOWN-level	less than 1%	less than 1%
Inverter, Non-saturating T_F	2%	8%
T_{DF}	less than 1%	5%

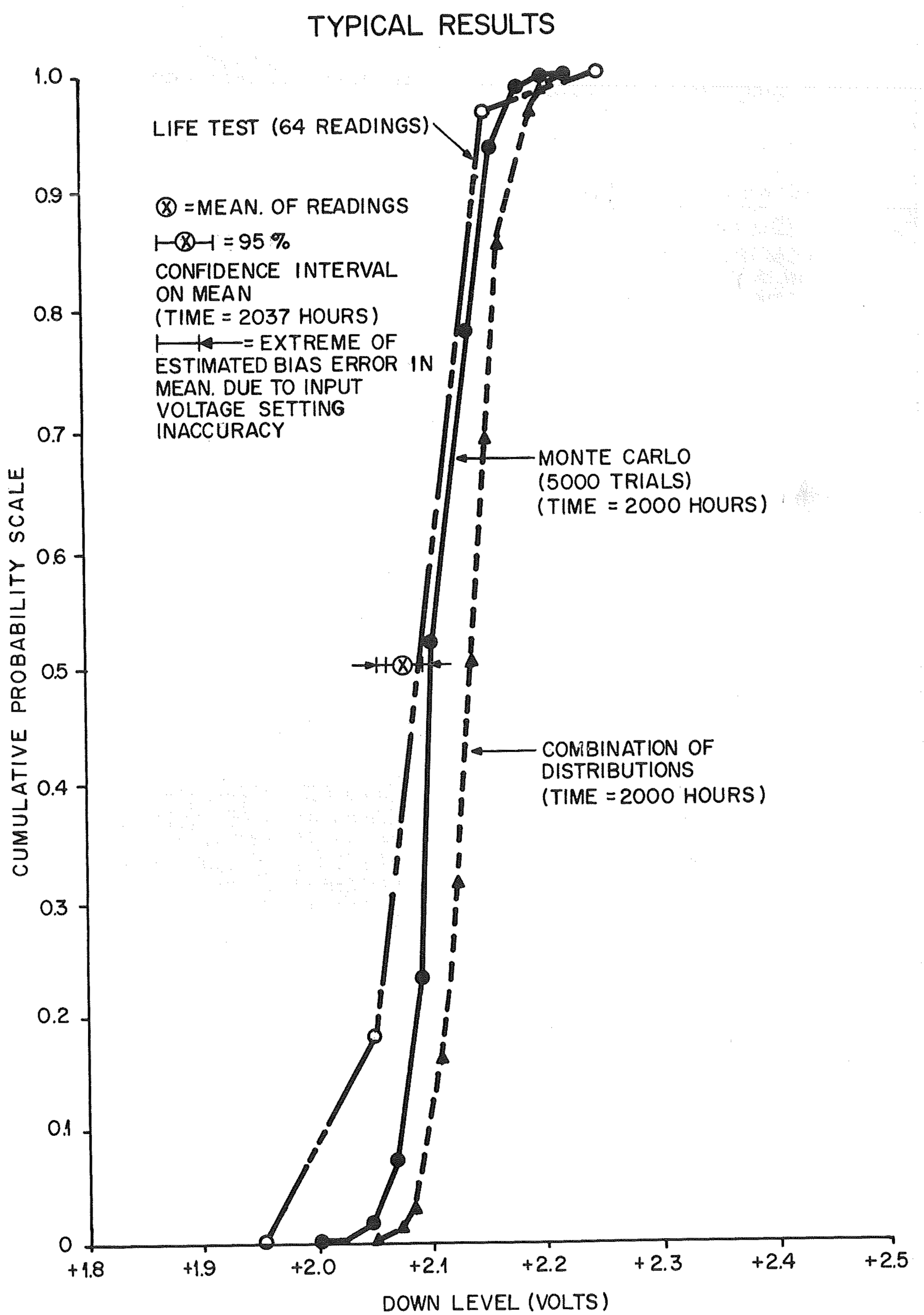


Figure 1. OR-Gate Circuit, DOWN-level Cumulative Probability Polygons

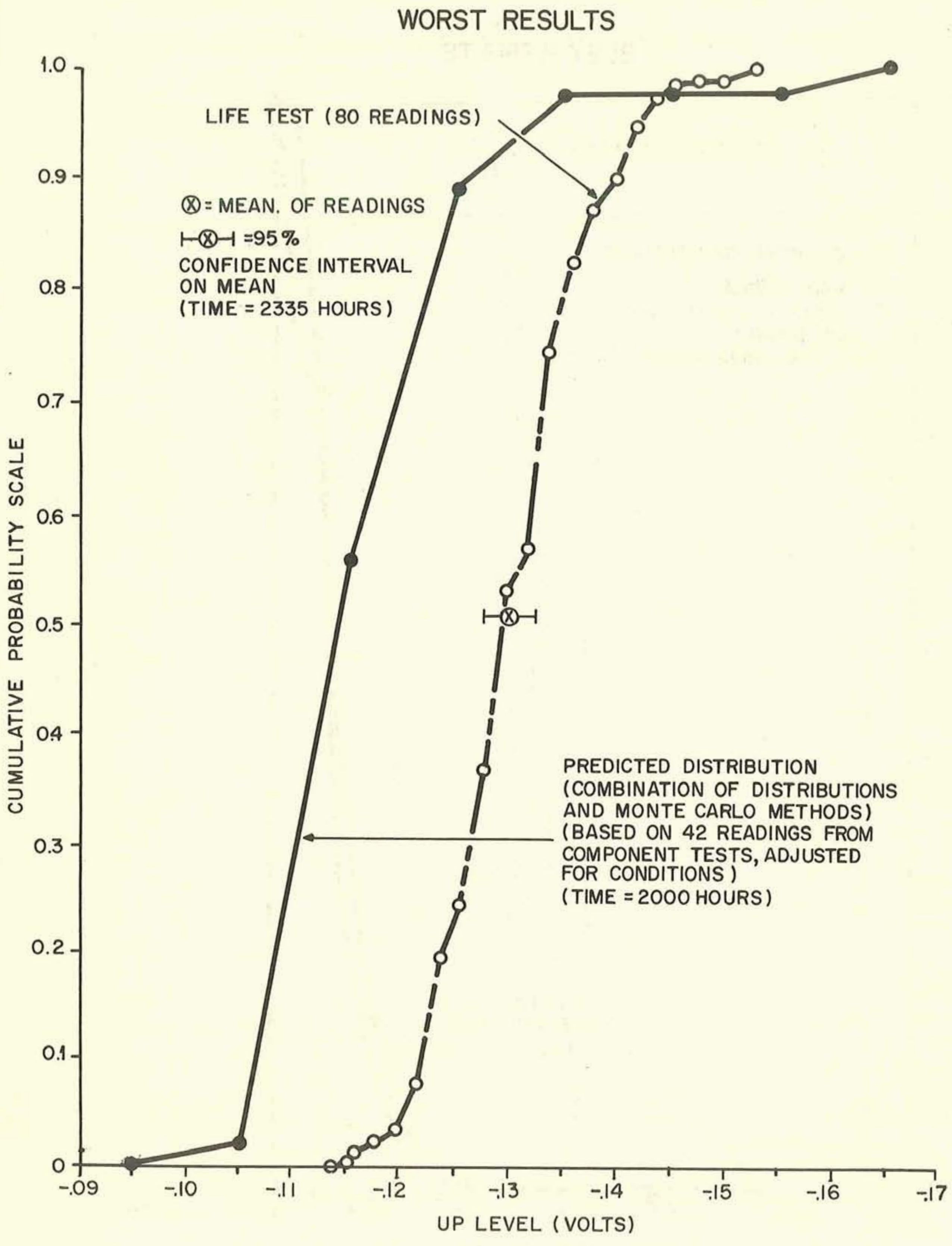


Figure 2. Saturating Inverter Circuit UP-level Cumulative Probability Polygons

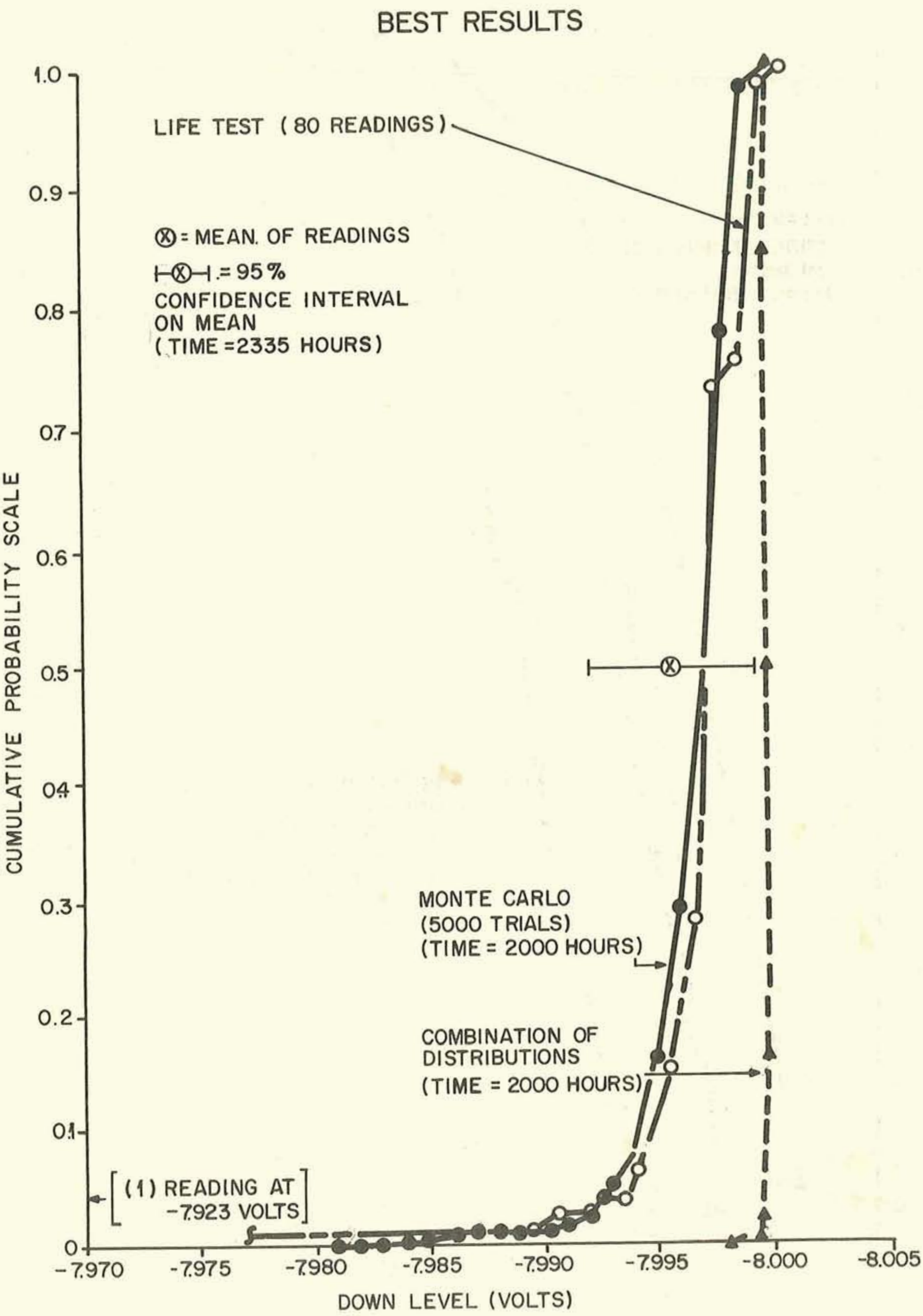


Figure 3. Saturating Inverter Circuit DOWN-level Cumulative Probability Polygons

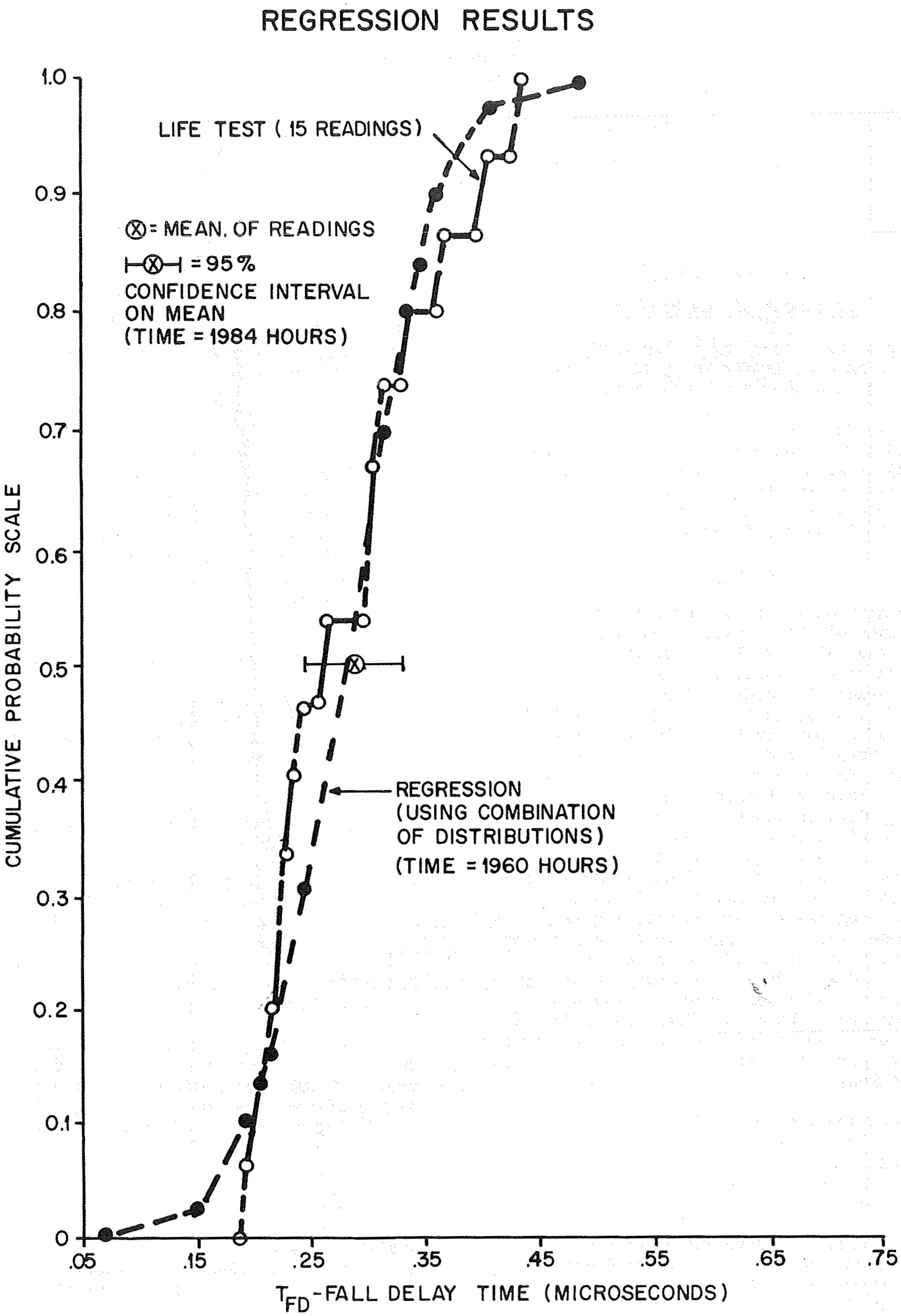


Figure 4. Non-Saturating Inverter Circuit, Fall Delay Time (T_{DF}) Cumulative Probability Polygons

THE SPECIFICATION AND ASSURANCE OF LARGE MTBF'S TYPICAL OF SPACECRAFT ELECTRONIC EQUIPMENTS

Clifford C. Petersen
Motorola Inc.
Military Electronics Division
Western Center
Scottsdale, Arizona

Statement of the Problem

While this paper may be regarded, in a sense, as an open letter to systems managers from one of the many suppliers of electronic equipments for spacecraft, the topic is of wide interest. The aerospace industry is confronted more and more frequently with the following question related to complex equipments of the type normally procured in small quantity for use in spacecraft systems; the question is: "How is reliability best specified and assured?"

Assurance

We must deal with the question of assurance before that of the specification of reliability because the latter will reflect the amount of assurance that is wanted. There is little doubt that assurance is needed, since it is the logical basis for making many decisions in the genesis of a space system. Without assurance we are forced into decisions based on hope or judgment. The Department of Defense is talking loud and clear about incentive plans for reliability.[1] Certain Congressmen are speaking of having manufacturers post bonds which would be forfeited if their equipment failed during countdown or in space operations.[2] Many manufacturers have had experience with costly modification programs to correct unreliability. From these facts it is clear that assurance is needed by both the manufacturer and the customer. However, assurance must be timely, available in sufficient degree at the time decisions are to be made. There is no justification for spending funds for assurance intended merely to give an after-the-fact sense of satisfaction.

There are many ways of assuring that an equipment is, or will be, reliable. They differ in degree as well as in technique and are fully explored in the literature of the day. They include implicit confidence in predictive estimates based on part counts, trust in the implementation and surveillance of special design and manufacturing practices, reliance on product improvement achieved by overstress testing to failure, and the demonstration of mean time between failures by life test. These techniques are used singly or in combination to create confidence at a time prior to actual countdown. The life test technique usually gives the most confidence. In spite of some obvious problems, we believe demonstration by life test should be a mandatory technique for generating assurance, even for large mean times between failure.

Demonstrated Assurance

The MTBF's required of spacecraft equipments usually are large. Requirements we encountered a year or two ago were stated in terms such as 90 per cent reliability for a one-year mission for equipments intended for Advent, OAO, and OGO. More recently we have bid on equipment having reliability requirements stated in terms of large MTBF's. Typical are:

Deep Space Communications System for Apollo -
5,200 hrs, design goal

Minitrack Beacon for Apollo -
16,750 hrs, design goal; (8820 hrs of test experience, no failures)

S-Band Beacon -
5,000 hrs, requirement; 15,000 hrs, design goal

Data Reception System for Gemini -
16,800 hrs, requirement; requires test of 3 systems for 16,800 accumulated equipment hours.

Radar Set for Space Seeker Satellite -
10,000 hrs, requirement.

When we think of accumulating many equipment-years of controlled life test data in order to demonstrate MTBF's like these with high confidence we are shocked. Usual scheduling practices are such that there is too little time before expiration of contracts to perform such demonstrations. New developments typically run a year or two and modifications of present devices are usually wanted in less than one year. Also the present state of the art of accelerated test techniques is too undeveloped to alleviate the situation. We will now suggest several means of mitigating this problem.

Making Demonstration Possible

One possible way to gain time for lengthy demonstration is to extend the contract given

to the equipment developer to a time beyond the delivery dates of deliverable items, and make it extend to the latest possible time when a firm reliability assessment is required. This would permit the longest possible duration of reliability demonstration tests. It also assumes that the information will be useful in decision-making after delivery of equipments. We believe that it is not too late to apply demonstrated results to decision-making up to the time of blastoff, whether these be decisions regarding launch operations, modifications, or contract incentive payments.

Another means of gaining time is to ask that manufacturers who supply basic equipments with minor modifications show evidence of long duration life tests which they have previously conducted on their basic product. Progressive manufacturers with so-called off-the-shelf items should feel the real need to know the MTBF of their equipments for their own assurance, as well as for improving their prospects of gaining new contracts. So much time is often spent mulling over such a step that it is well for manufacturers to remember that a test never started is never finished.

Yet another alternative, if time absolutely does not permit demonstrated assurance with a high confidence, is to call for the performance of life tests of whatever duration is feasible, even though not long enough to provide full confidence. Increasing the number of equipments to more than the few usually subjected to life test seems highly desirable. Testing such increased quantities for one-half, or one-quarter, of the mission time would provide a fair degree of confidence. While such a test would not demonstrate longevity, it would produce a more satisfactory number of equipment-hours and would permit surveillance of a more representative sample. To avoid life or reliability tests entirely because a truly adequate test cannot be conducted would be an error. Our experience has shown that much is revealed fairly early in an equipment or system life test, giving knowledge of a type not uncovered in typical equipment qualification tests.

Specification

The specification and schedule should be consistent with a course of action selected from the suggestions just presented. The schedule, should, insofar as practical, allow adequate time for the discovery and correction of equipment design deficiencies. The system manager, in requiring a demonstration by test during the course of the contract, should specify the duration of the test, conditions of test (preferably selected from standard AGREE levels), the number of equipments to be tested, and the number of allowable failures. He is in the best position to determine tradeoff between schedule and confidence. If he leaves the design of the demonstration test to the equipment supplier, bids will reflect various interpretations of this costly task.

The specification should also include other often neglected means of adding to reliability assurance. Three such means seem worthy of discussion.

Parts standardization should be implemented on a systemwide basis whenever possible. The advantages are so tremendous that full consideration should be given to requiring the use of specific component parts that have proven merit or that will be so established in a coordinated test program. Reducing the variety of types, values, and makes of parts makes it possible to conduct strong efforts in improving them, in screening them, in determing their failure rates, and in understanding their limitations and behavior as basic building blocks. Standardization is not easy. Equipment producers have their own preferences, and strong, early leadership must be taken in such a standardization effort. We have seen a few such attempts fall on their face principally because they were of an optional nature or because they were not started soon enough. Admiral Horne, in the keynote speech at the Eighth National R & QC Symposium, endorsed a recommendation by an Electronic Industries Association committee to the effect that the number of types and values of parts now being used should be reduced drastically. When parts with guaranteed levels of failure rate are available, through implementation of the Darnell report, it may become easier to standardize within a system because the vendors of parts will, in effect, be classified as to reliability. By requiring that procurement be to a specified reliability level, the variety of part types and vendors in use in the system will be narrowed. We note a recent trend toward a degree of standardization through the easily stated edict to "use Minuteman grade parts." A word of caution is appropriate on this score. Not all users are aware that a great deal of screening and burn-in testing is performed on such parts by the purchaser before being installed in Minuteman equipments. While it is true that a certain amount of product improvement advantage and a narrowing of part varieties is achieved by attempting to use "Minuteman parts," we feel that the reliability advantages to the casual user have been oversold.

The second neglected area relates to orientation of designers with respect to the field use conditions. Principal designers should be shown systems mockups, given first-hand opportunity to see where their equipments are bolted into the system, and taken on-site to witness typical end use conditions. Merely specifying environments and operating periods is rather inadequate in conveying to the designer a retainable picture of the kind of operating, handling, and checkout abuse to

which his equipment will be subjected. Proper orientation of designers will provide additional assurance that designs will be compatible with use conditions and thus more reliable.

The third neglected area concerns field failure removal and analysis activities. The equipment manufacturer should be included in these operations as he is in the best position to detect possible deficiencies of his electronic equipment and to gather complete information needed for the analysis and corrective action decisions. It is no secret that failure analysis of deficiencies occurring in the field is far from optimum.[3] On the spot troubleshooting by the equipment manufacturer and return of unmolested equipments to his plant for further analysis and repair would add to assurance that reliability objectives would be more quickly achieved.

Longer Burn-In

So far in this talk we have attempted to establish that reliability assurance is needed, that systems specifications should require several often neglected means of increasing assurance, and that demonstration life tests should not be eliminated, even though finding sufficient time to perform the tests is a difficult problem. In stating that such tests naturally take a long time, it is implied that accelerating techniques are not presently valid and that previously accepted experience and theory regarding the constant failure rate of electronic equipments applies to typical spacecraft missions. We will now discuss the implications if a decreasing failure rate, rather than constant failure rate, were actually applicable to long term space missions, and present some facts that indicate this may be the case. A decreasing failure rate, of course, would point to the advisability of longer burn-in periods. It also would shorten the demonstration test, or looking at it another way, would give more confidence with a given duration of test. A possible curtailed demonstration test for a typical spacecraft MTBF could be as follows. It could require 5 to 10 equipments to be burned-in for 1000 hours each at AGREE X-level, during which period failures would be analyzed but not be considered as deficiencies. Presumably the decreasing failure rate would be confirmed during the burn-in period. All equipments could then be required to survive the next 2000 hours of test at the less severe AGREE M-level with perhaps no more than one failure permitted during the 10,000 to 20,000 equipment-hours of test. If marginal parts were replaced during the long burn-in, and only one failure occurred during the 2000-hour test, there would be additional basis for confidence that the failure rate was decreasing and that longer missions could be accomplished with very low probability of failure by equipments that had been properly burned-in.

The Case for Decreasing Failure Rate

The concept of constant failure rate being characteristic of complex electronic equipments started as a result of early field studies by ARInc and others. Experience still shows that when equipments are repaired as they fail, particularly when this occurs frequently, part ages become mixed and the constant failure rate is a good approximation for equipments. As a result of this, the convenient thing to do is assume that parts also must have a constant failure rate, and this gives birth to a flurry of activities in reliability prediction with refinements that are of questionable merit.

Horn and Shoup of Boeing[4] have analyzed the failure rate of B-52 systems versus mission time and found that 2-hour flights experienced failure rates of 34% per hour, while missions of 10 to 24 hours had failure rates of 1% per hour. These figures are cumulative for many systems of the airplane but the electronic systems followed this same trend. The effect is attributed to turn-on stresses, take-off environment, and the consequences of poor maintenance making themselves felt to a greater degree on short missions.

Remington Rand Univac, in private communications, indicates that published data on their Athena computer system shows a steadily decreasing failure rate, now less than 1% per million hours per part. This computer has long operating periods, few failures, and a mild environment; it thus has some of the characteristics of space flight conditions.

The evidence is stronger for parts. Procassini and Romano of Motorola[5] have demonstrated with very extensive tests (20,000 hours in duration) that germanium switching and amplifier transistors clearly follow a Weibull failure distribution with decreasing failure rate. The Weibull β parameter ranged from 0.1 to 0.4. This work showed that a stated Minuteman goal of .0007% per thousand hours during a three-year period should more properly be defined as a cumulative percentage of failures to be allowed in this period. As stated, a constant failure rate is implied, whereas it was proved that on specific test lots the early failure rate was higher than the goal and the final failure rate was lower than the goal.

At Motorola, we also have data on 10,000- and 15,000-hour tests[6] of deposited-carbon resistors, silvered mica capacitors, and paper capacitors, that distinctly show diminishing failure rates as time is extended. Often we have found at the end of long term tests that the surviving parts, instead of being worn out or unreliable, are really just well broken in. Hines of Corning Glass Works[7] presented the results of over 166 million unit-hours of tests on fixed glass capacitors early this year. The

failure rates observed were strongly decreasing after about 1500 hours and were well described by a Weibull distribution with $\beta = 0.4$. Hines made a strong plea that we cease "the practice of blindly assuming an exponential failure distribution," or constant failure rate. Weaver and Smith of Minneapolis-Honeywell[8] have shown that gyro spin motors exhibit decreasing failure rates (Weibull distribution with $\beta = 0.65$) up to the time wearout mechanisms take effect. L. R. Goldthwaite of the Bell Laboratories[9] suggests that what we have been calling exponential failure distributions with constant failure rate may actually be log normal distributions which have decreasing failure rates after the mode has been reached. The two distributions are easily confused if the data is meager.

If decreasing failure rates are generally applicable to parts, then equipment design efforts that are strongly oriented toward reliability should produce equipments having decreasing failure rates. On such well-designed equipments, relatively few parts would be replaced, even in the burn-in period. The effects of poor maintenance would be eliminated because repair during burn-in would be accomplished in-plant.

Needed Research

At present it appears that we should obtain our fullest assurance of reliability by life testing and longer burn-in of equipments and systems. Because of the considerable cost in dollars and hours required for doing this, however, it is imperative that we devise means of accelerating tests, improve the accuracy of our predictive estimates of reliability, and gain the capability of identifying and screening out parts having less than average potential lifetimes.

We must learn how to sufficiently and validly accelerate tests on equipments and parts. Attempts to do this on equipments have been rare. More work is needed such as the effort by Pettinato and McLaughlin[10] which resulted in determining an acceleration factor of 2.3 for communications equipment when the ambient temperature was increased from 25 to 70°C. Acceleration attempts on parts have led to conflicting results and to many claims that they are not valid because the methods induce non-typical failure modes. More fundamental work in this area, such as that being done by the Battelle Memorial Institute under sponsorship of the ECRC,[11] should be encouraged.

We should determine more accurately what failure distributions really are applicable to parts, equipments, and systems so that our predictive estimates will be based on fact, not convenience. If the exponential distribution is found generally non-applicable, then we will need to perfect practical methods of calculating reliability from the combined effects of parts having many different types of failure distributions.

It's imperative that we search further into the material behavior associated with failing component parts so that we identify the mechanisms of failure. Such knowledge would permit us to more effectively apply predictive screening techniques for which statistical methods are already highly developed.[12] This knowledge of failure mechanisms would also lead to a better choice of stresses in our attempts to accelerate life testing.

We should gather reliable data on the occurrence of part failures in the various failure modes. This information is necessary if we are to apply redundancy effectively at the part level. Whether, for example, a resistor fails by shorting more often than it fails by opening a circuit determines whether redundant resistors should be in series or in parallel. A mistake in our assumption could result in making the circuit less reliable, and of course our predictive estimates would also be erroneous.

Success in all these areas of research would increase our ability to design more reliable equipment and make it possible for us to gain needed assurance of reliability, at an early time, by test and by more accurate predictive estimates.

Summary

17288

The initially stated question relative to large MTBF's typical of spacecraft missions was, "How is reliability best specified and assured?" We have answered as follows: assurance by means of life test demonstration is the best kind of assurance even if such tests must be curtailed; several ways of making long tests practicable were suggested; some often neglected specification requirements were discussed; and the implications of a decreasing failure rate and longer burn-in of equipment were explored. Finally we suggested that research be vigorously pursued in the following areas:

- Development of accelerated test techniques.
- Determination of actual failure rates.
- Understanding of failure mechanisms and application of this knowledge to screening techniques.
- Data collection on failure modes to aid redundant design and predictive estimates.

Improvement in our present methods of gaining assurance of reliability will become a necessity as space missions and attendant mean times between failure become longer.

References

1. Thomas D. Morris, Asst. Defense Secy. for Installation and Logistics, Electronic News, 2/5/62.

2. A.S.A. Newsletter No. 107, March 1962.

3. Battelle Memorial Institute, Technical Memo No. 3, ECRC, "Survey of Field Failure Reporting Systems," 7/5/60.

4. Horn and Shoup, "Determinations and Use of Failure Patterns," Proc. Eighth National Symposium on Reliability and Quality Control, January 1962.

5. Procassini and Romano, "Use of the Weibull Distribution Function in the Analysis of Multivariate Life Test Results," WESCON, August 1961.

6. Motorola Military Electronics Division, Reliability and Components Group Reports No. M-517R-17 and M-517-19, and IDEP No. 151.45.00.50-E9-01.

7. L. D. Hines, "Acceleration Factor Determination on Glass Capacitors," Proc. Eighth National Symposium on Reliability and Quality Control, January 1962.

8. Weaver and Smith, "Life Distribution of Electromechanical Parts," Proc. Eighth National Symposium on Reliability and Quality Control, January 1962.

9. L. R. Goldthwaite, "Failure Rate Study for the Lognormal Lifetime Model," Proc. Seventh National Symposium on Reliability and Quality Control, January 1961.

10. Pettinato and McLaughlin, "Accelerated Reliability Testing," Proc. Seventh National Symposium on Reliability and Quality Control, January 1961.

11. Battelle Memorial Institute, Research Report No. 5, Electronic Components Reliability Center, February 28, 1962.

12. Battelle Memorial Institute, Technical Memoranda No. 5, 8, and 10, and Research Report No. 1, ECRC, November 1960 - September 1961.

RELIABILITY PROGRAMS FOR "L" SYSTEMS

James R. Barton
Major USAF

George H. Allen
Staff Reliability

Electronic Systems Division
Laurence G. Hanscom Field
Bedford, Massachusetts

17289

Summary

The AFSC Program Structure assigns numbers and letters to the various programs in order to identify the efforts for management control. The fact that most of the command and control systems have the designator "L" affixed has prompted the reference to them as the "L" systems.

In this paper the mission of "L" systems has been described, the complexity of the equipment indicated, and the importance of these systems to our national defense efforts pointed out.

The efforts by the Electronic Systems Division to comply with the Air Force policy that a comprehensive reliability program be required for each contract to assure delivery of reliable systems and equipment to the Air Force inventory are described in considerable detail.

Definition and Mission of "L" Systems

The breadth and variation of the Air Force Systems Command's efforts require a means of categorizing this effort into subelements for management and control. The AFSC program structure was developed to provide the criterion whereby each AFSC job is categorized and identified. The systems which this paper will deal with are those of the "L" systems which are categorized in the program structure PS 400L through PS 499L. The command and control systems, often referred to as "L" systems, are composites of equipment, skills, and techniques which, while not instruments of combat, are capable of performing the clearly defined function of enabling a commander to exercise continuous control of his forces and weapons in all situations by providing him with the information needed to make operational decisions and the means for passing on these decisions.

These systems are extremely complex with parts counts of some totaling 450,000,000 parts. While the use of parts count as an indication of system complexity may be somewhat misleading, it can be seen from the enormity of the number alone that these systems are tremendous in size and complexity. For systems designed to perform such an important function in our defense system, it is easy to see why reliability has become such an important design factor and why the achievement of reliability could be such a problem.

A complete system includes all subsystems, related facilities, equipment, materiel, services, and personnel required for operation of the system so that it can be considered a self-sufficient unit in its intended operational environment. The mission of these systems may then be stated as that of collecting, transmitting, processing, and displaying information for command decisions and for control of forces, weapons, and aerospace vehicles. From this simple mission statement of the systems developed by the Electronic Systems Division (ESD) we get a vivid picture of the importance of this work to the defense and survival of our nation and our allies. Without these systems there could be no early warning, detection, interception nor destruction of aggressor weapons in time to prevent destruction of our nation and resources.

To develop these systems various USAF organizations have been amalgamated into a well coordinated team at Laurence G. Hanscom Field in Bedford, Massachusetts to provide a concurrent approach to the task of providing electronic systems for command and control of aerospace forces. This team is comprised of representatives from research and development, logistics, training, and using commands with specific system acquisition responsibilities being assigned to a specific System Program Office (SPO) identified by a program structure designator between 400L and 499L. Technical support of the program is provided by the Rome Air Development Center (RADC) at Griffiss A.F.B., Rome, New York and non-profit organizations such as MITRE. The officer in charge of the SPO has the official title of the System Program Director and as such is charged with the responsibility to develop, and to deliver the first complete system to the using command on schedule, at the lowest price possible and with the highest practicable capability and reliability.

Reliability Requirements

In recognition of the importance of the

design for reliability, Headquarters USAF published a regulation, AFR 375-5 entitled: Reliability Program for Weapon, Support and Command and Control Systems, which defines reliability as the probability that a system will perform a required function under specified conditions, without failure, for a specified period of time. This regulation also clearly enunciates the Air Force policy on reliability. Briefly stated, the Air Force requires that reliability be considered as a major design factor to be stressed during early system studies, source selection, design, development, and production. Each program for which a contract is written shall include realistic reliability requirements expressed as numerical probability values from the minimum acceptable to the desired goal, with such intermediate quantitative values required to measure progression, and a stated minimum acceptable confidence level for each probability value. These reliability requirements will extend through the system contractor, subcontractor, and vendor levels with monitoring points established in order to assist the Air Force in surveillance of the program through all phases of development and production.

It is evident from the brief statement of the Air Force policy on reliability that great emphasis is placed upon quantitative requirements in contracts for equipment or studies in which the Air Force will have an equity. We at the ESD hold that it is just as important that these numerical statements of reliability requirements be realistic. Further, the upper value established as a goal should be such that a constant advancement in the state-of-the-art is made by requiring greater refinement of methods, techniques, and components to achieve these goals. To provide realistic values for new equipments performing new functions is difficult and it is in matters of this type that the technical support of the Rome Air Development Center (RADC) is relied upon. In the search for more realistic reliability requirements, it has become increasingly obvious that reliability alone does not totally meet the "L" systems requirements; therefore, the requirements have been more and more stated in terms of availability where not only reliability is a prime engineering factor, but maintainability becomes increasingly important. The use of the availability figure of merit permits trade-offs between reliability and maintainability, thus making possible the selection of optimum values of each to be achieved while considering the total life cycle of the equipment. Such total considerations result in more Air Force per dollar and at the same time provides the high level of mission capability required by our customers, the using commands.

While this paper primarily deals with reliability, it should be borne in mind that in each instance where reliability is used the word maintainability could be inserted with equal application and importance.

Integrated Missile and Command and Control Systems

Before the regimen is described to you, by means of which the reliability and/or maintainability programs are administered at the ESD, it might be well to discuss very briefly a system developed by the ESD. The systems with which most of us are familiar at this time are the Ballistic Missile Early Warning System (BMEWS) and Semi-Automatic Ground Environment (SAGE).

The SAGE/BIRDIE/NIKE System is a good example of an integrated missile and command and control system. For those of you not familiar with the BIRDIE equipment, BIRDIE stands for Battery Integration and Radar Display Equipment. This equipment provides the connecting link between the SAGE system and the non-Missile Master equipped surface-to-air missile fire unit complexes and are designed to permit effective battle application of Army provided missiles through North American Air Defense (NORAD) direction from SAGE facilities by digital communications and electronic designations. The primary purpose of the BIRDIE equipment is to integrate the air defense artillery (ADA) units with SAGE to provide data interchange between fire units and to enable the ADA defense commander to monitor the air battle.

This integrated SAGE/BIRDIE/NIKE system provides an excellent comparison of the strategems available to the engineer to achieve the high degree of reliability required of these systems. The SAGE system provides a single channel of operational control extending from NORAD Combat Operations Center (COC) down to SAGE regions and sectors. This concept of operation dictates the vesting of operational authority of the whole defense system in a centralized agency having complete cognizance of the air situation. Within these concepts the SAGE/BIRDIE/NIKE system must function so that adequate utilization of Air Defense Artillery weapons may be accomplished with respect to other weapon systems. To achieve the positive control with the necessary assurance that these functions will be performed, it is essential that delegation of defense responsibilities and modes of operation be enunciated. To accomplish the SAGE mission, there are four modes of operation. The nominal mode of operation or Mode I is that each SAGE Direction Center (DC) will be responsible for and will exercise complete control over the conduct of the air battle within its sector boundaries. Mode II - when any DC becomes inoperative, adjacent DC's will accept full air defense responsibilities and authority over specified portions of the disabled DC. Mode III - in the event of two adjacent DC's becoming inoperative or any other situation develops that prevents Mode I and Mode II operation the Norad Control Center (NCC) will assume responsibility and operational control within their specified areas. Mode IV - in the event that any air defense weapon system or unit loses all contact with the SAGE DC or NCC

under whose control they were previously operating they will operate autonomously under such local control as may be operative within the system or unit with responsibility for control vested in the local unit or weapons system commander.

It can be readily perceived from the described modes of operation that the system provides parallel redundancy in the paths that may be utilized to exercise control over the weapons. While some degradation may be suffered in switching to alternate modes, the probability of successfully accomplishing the required mission is very high. When it is considered that this portion of the system is in series with the weapon and warhead probabilities, it is apparent that a high probability is required. The use of high yield atomic warheads would raise the probability of kill, provided the delivery of the device within a given distance, to virtually 1.00 probability.

The third element in this series system is the vehicle itself. The probability that the firing from the point of liftoff and trajectory to the target area is the lowest value of the series, but it must be realized that this probability can also be improved upon by redundancy. Assignment of additional weapons to the same target will increase the probability of success for intercept and kill. From this example, it can be seen that the reliability of ground electronic equipment permits the use of less reliable subsystems that are non-recoverable or one-shot units. This in itself will provide the choice of utilizing the more refined or developed equipments where it can be repaired and returned to service.

General Implementing Documents and Philosophy

The SAGE system has served as an example of what has been accomplished by the ESD and we now turn to the present and future efforts. The AFR 375-5, Reliability Program for Weapon, Support, and Command and Control Systems, established the requirement for quantitative statement of reliability goals and minimum acceptable reliability levels. It is now important that we examine the vehicles available to us to achieve these goals. Prior to the publication of this regulation, there were in existance specifications and standards that had evolved from the Advisory Group on Reliability of Electronic Equipment (AGREE) Report, and various exhibits developed by different centers and divisions such as the Aeronautical Systems Division, Ballistic Systems Division, Electronic Systems Division, and the Rome Air Development Center. These specifications, written to provide the framework for our reliability programs, were modified, consolidated, rewritten, and submitted to industry for their comments and/or recommendations to provide a general document that would reflect the latest thinking of agencies involved directly or indirectly with complying the stated requirements. These specifications, as they are today, constitute the tools available to us to implement a comprehensive reliability program for our systems. There are numerous specifications published on reliability, but the ones used by the ESD have been narrowed down to MIL-R-27542 (superseding MIL-R-26674), Reliability Program Requirements for Aerospace Systems, Subsystems, and Equipment; MIL-R-27070, Reliability for Development of C-E Equipment; MIL-R-26474, Reliability for Production of C-E Equipment; MIL-R-26667A, Reliability and Longevity Requirements, Electronic Equipment, General Specification for; MIL-Std-441, Reliability of Military Equipment; USAF Bulletin 506, Reliability Monitoring; USAF Bulletin 510, Reliability Organization; and MIL-Q-9858, Quality Control System Requirements.

These specifications are by necessity general in nature and are written to be equally applicable to electronic, aeronautical, ballistic, and space systems. For this reason, ESD has found it necessary to supplement the instructions contained in these specifications with more explicit guidance in the preparation of requests for proposals (RFP's), contractor Reliability/Maintainability Plans, etc. In addition, ESD recognizes that contractor guidance must be provided in the form of briefings for all bidders. When a contractor has been selected, ESD provides more explicit instructions and direction in order to obtain the type of program needed by the Air Force to support the design and development of a specified system. This guidance provides a firm requirement for specific tasks to be accomplished by the contractor, time phasing of events, Air Force contractor monitoring procedures, and methods of communication.

Bidders' Briefings. ESD expects to have and has had participation by Staff Reliability coordinators in bidders' briefings. The purposes of this participation are to: (1) review, interpret, and answer questions on the numerical reliability requirements; (2) explain overall ESD reliability philosophy; and (3) outline and recommend the type and quantity or depth of reliability information needed for evaluation of bidders' reliability proposals.

This latter information usually includes: (1) a prediction of the reliability of the proposed system and any alternate systems; (2) the reliability organizational structure and the lines of communication between management and reliability, design engineering and reliability, manufacturing and reliability, test engineering and reliability, etc.; (3) the corrective action loop; (4) the design review structure, its authority, and modus operandi; (5) a description of the experience and achievements on past programs which involved numerical reliability requirements; and (6) where possible, a comparison of unit operational or achieved MTBF's on similar systems with predicted unit MTBF's on the proposed system or systems.

The reliability proposal material of the successful bidder will serve as the contractor's major input to the reliability guidance meetings to be discussed in the next paragraph.

Contractor Guidance Meetings. ESD is utilizing reliability specifications in their various "L" system programs. Since, as mentioned earlier, these specifications are written in a manner which affords interpretations as to content and work scope per system program, ESD conducts reliability guidance meetings for the contractor. The main purposes of these meetings are to establish the: (1) series of tasks or work items which will define or constitute the contractor's formal reliability effort. The basis for these tasks is expected to be found in the contractor's reply to ESD's RFP and the basic reliability specifications stipulated contractually; (2) task descriptions, calendar time durations, and manpower necessary to perform each task; (3) ESD/Contractor monitoring at reliability program review points; the number of review points will be a function of the importance, scope, and overall duration of the system program; (4) contractor control techniques for subcontracting reliability activities; and (5) schedule and content of reliability reports to be submitted to the ESD.

Secondary purposes of these meetings are to: (1) establish the reliability lines of communication between ESD and the contractor and his subcontractors; and (2) identify contractor and ESD personnel involved in the reliability effort and their respective responsibilities. Perhaps the most obvious fact about planning for the attainment of system reliability is that there are numerous places during a system program at which unreliability can creep in strictly from faulty communications between the agencies involved in bringing a system into the USAF inventory.

Referring to the first main purpose of the guidance meetings, the use of the word formal serves a particular objective; namely, to indicate that the contractor's responsibility for reliability activities must extend beyond the performance of his reliability tasks into all his engineering, technical support, and management activities. Reliability must be considered in all the decisions and resulting actions in order that a system will be delivered to USAF which satisfies or exceeds the numerical reliability requirements. Under this philosophy of operation, the formal reliability effort is placed in proper perspective: it is a series of tasks which assist in but do not guarantee the delivery of a reliable system and which must not only be integrated within the whole family of contractor tasks but also must influence the manner in which these tasks are performed.

The interaction and dependency of contractor tasks are brought out during guidance meetings. As examples, ESD usually negotiates a line item or task within the formal reliability program which requires that the contractor's reliability organization conduct a malfunction data collection and feedback system. The existence of this task is partially justified since it supports the overall corrective action process. Therefore, its weak-link identification output must be utilized by reliability and other agencies responsible for corrective action within the contractor's overall organizational structure. The requirement for predictions of system reliability during the design phase of a system program requires the contractor's design engineering agency to supply actual component part application margins of safety to his reliability organization. ESD does not expect that the reliability organization will be required to compute actual component part margins of safety but will review and utilize the information available from the design process itself. As we will mention later, ESD expects the reliability organization to participate with design engineering in the selection of part application margins of safety.

A clear representation of the contractor's control techniques for the reliability activities of his subcontractors is viewed as necessary for contractor management of "L" system reliability programs. Similarly, the establishment during guidance meetings of monitoring or milestone points between ESD and the contractor and the general type and depth of information to be made available for ESD review at these meetings is necessary for ESD reliability management. In addition, the regular submission to ESD of reliability reports is another management control technique.

The final output of guidance meetings is the submission to and approval by ESD of the contractor's formal reliability program plan.

Reliability Specifications and Some Resulting ESD Requirements

At this time, let's consider several of the reliability specifications which have been employed by ESD on past system contracts and some resulting ESD requirements based on these specifications. The manner in which these specifications and related tasks are to be employed on particular system programs will be determined by ESD prior to the briefing and guidance meetings on reliability.

a. MIL-R-27070, Reliability for Development of C-E Equipment

This specification requires a contractor to perform the following tasks: (1) system reliability predictions; (2) reliability indoctrination of key contractor personnel; (3) prime contractor plan for control and direction of subcontractor reliability activities; (4)

critical and/or limited life component part studies and application recommendations; (5) program and implement techniques for designing-in reliability; (6) reports to ESD; and (7) reliability demonstration tests.

In performing reliability predictions and submitting prediction reports to ESD, a contractor must indicate all mathematical equations, including the derivation of any original mathematical expressions and the source of failure rates and K factors employed in making the predictions. If failure rates peculiar to a particular contractor are utilized in predicting, in lieu of "standard" failure rates contained in the RADC Reliability Notebook, for example, ESD requires statistical and engineering descriptions of the methods involved in collecting and reducing the data to failure rate form.

The reliability design techniques described in this specification are considered to be the basic means by which reliability can be designed into an "L" system. These techniques can be grouped conveniently into three general categories: (1) conservative selection and application of piece parts; (2) minimization of environmental influences; and (3) use of redundant functional replacements and/or alternate modes of operation. The last technique is generally applicable for "L" systems which are not extremely restricted by weight and volume considerations and which, in terms of numbers of functional parts, are highly complex.

While the specific reliability design techniques to be employed per program are dependent on the overall system mission requirements, it is a basic ESD reliability policy that all component part applications must receive adequate margins of safety in order to minimize the probability of system failure from nickel and dime sources. This reliability policy has been supported by the publication of the RADC Reliability Notebook which presents component part application interaction models (stress vs failure rate) and recommends regions for reliable operation. In selecting component part vendors, ESD expects a contractor to be guided by his past failure rate experience on other system contracts, his incoming inspection test records, his periodic vendor qualification reviews, and standard part lists.

A contractor's overall plans for designing reliability into "L" systems are receiving considerable review and auditing by ESD. Audits will be concerned with such things as how a contractor, with a proposed system design which incorporates limited life or high failure rate items such as a klystron and/or magnetron, plans to introduce compensating reliability factors into his system design in order to minimize the influence of these items on the overall system failure rate.

Several ESD reliability programs have already begun to require the submission of a "Reliability Design Handbook." Each handbook is actually a specified plan for designing reliability into a system and, therefore, discusses planned minimization of operational stress techniques, part application margins of safety, etc.

With regard to reliability indoctrination of key personnel, a contractor is expected to <u>supplement</u> previous reliability education negotiated on other programs with a minimum number of lectures, pamphlets, posters, etc. ESD usually requires that all lecture notes and list of attendees be made available upon request.

Since several items (reliability testing, reports) of MIL-R-27070 are common to other reliability specifications, comments on these items will be presented during the discussion of these specifications.

b. <u>MIL-R-27542, Reliability Program Requirements for Aerospace Systems, Subsystems, and Equipment</u>

For purposes of a brief discussion, MIL-R-27542 activity requirements can be grouped under several categories: (1) reliability program management; (2) parts reliability engineering; (3) systems reliability engineering; (4) failure analysis and feedback; (5) statistical engineering; (6) manufacturing support; (7) field support; (8) reliability tests and demonstration; (9) human factors engineering; (10) special studies; (11) reliability indoctrination; and (12) reports to ESD.

Reliability program management involves: (1) the development of a plan; (2) integration of that plan within the overall system program plan; (3) monitoring and review of the requirement work items or tasks; (4) modification of the plan as necessary; and (5) prime contractors plan for control and direction of subcontractor reliability activities. As we have mentioned before, in a prime contractor's reliability plan, the subcontractor control function and prime contractor monitoring points must be clearly defined for ESD. Since MIL-R-27542 does not specify any date from award of contract for submission of a plan, ESD usually make the submission requirement a maximum of fourty-five (45) days. The exact date will vary with the type and scope of a program and will be agreed to at the contractor guidance meeting.

Parts reliability engineering is mainly concerned with the selection and application of "L" system piece parts. In the area of system reliability engineering, ESD is interested in design reviews - type of reviews, timing or frequency, personnel involved, corrective action recommendations, assignment for follow-up of the recommendations, the

corrective action break-in points, and the quantitative effects of such corrective actions on system reliability.

Design reviews are expected to be performed with shifting emphasis and frequency throughout a program and their conduct is expected to be influenced by the design for reliability techniques planned in the "Reliability Design Handbook." ESD is interested in participating in the following formal types of reviews: (1) parts list; (2) stress analysis; (3) circuit; and (4) physical or mechanical.

Review of parts lists is aimed at verifying that parts planned for use in a system are capable of meeting the application requirements. At such a review, a contractor is expected to have available to support his selection such information as: (1) each part's electrical and environmental rating; (2) qualification test data; and (3) previous failure rate experience.

Stress analysis reviews assure ESD that an adequate margin of safety has been provided for each application. Adequate is dependent on the overall system reliability requirements. Circuit reviews assure ESD that circuits are not being incorporated into a system which are unnecessarily complex and prone to frequent critical type failures. Physical or mechanical reviews are for assurance that mechanical features such as brackets, mountings, bolts, etc. are adequate. They are also concerned with the review of cooling techniques and the number and location of test points. For circuit and mechanical reviews, a contractor's senior engineering and engineering management people are expected to participate.

While the above reviews are formal and preplanned, ESD expects continuous informal reviews and communication between design engineering and the reliability organization. For example, these informal reviews may take place as the result of in-plant failure information collected and processed during the manufacturing process.

All engineering change proposals (ECP's) submitted to ESD must contain a prediction of the quantitative effect of the proposed change on system reliability. A contractor must support his predictions by appropriate failure data and mathematical techniques. Therefore, to accomplish these predictions, a contractor must maintain throughout a program a mathematical model which presents a continuous representation of the reliability of his system. He maintains this model as part of his statistical engineering activities.

While failure data collection and analysis activities support the corrective action process by the identification of actual weak-links, they also enable the assessment of system reliability. Contractors are expected to maintain a current computation of system reliability throughout a program, to make comparisons of actual or achieved and required reliability, and to use these assessments, comparisons, and failure data to modify the mathematical model referred to above. Prime contractors are expected to act as the "data center" for all subcontractors and be able to indicate rapidly to ESD actual failure causes, failure patterns, densities, and modes throughout his entire system.

During contractor guidance meetings, the failure data feedback and assessment system and the corrective action loops will be discussed. A contractor's reliability plan will be required to contain these systems and loops.

The maintenance of a current mathematical model, the conduction of formal and informal design reviews, failure data analysis, feedback, corrective action follow-up, and review of ECP's are viewed by ESD as important <u>control</u> activities of a reliability program.

The need for a well organized quality control function during the manufacturing process is recognized by MIL-R-27542. A prime purpose of such a function is the minimization of the number of operational or field failures that will be classified as to cause - "manufacturing error." While inherent and manufacturing error failures regulate the delivered reliability, it is really operational reliability that is of concern to ESD. The latter quantity is influenced not only by inherent and manufacturing errors but also field handling and operational caused failures.

To help minimize the latter category of failure causes, the majority of "L" systems have designed or built in a certain amount of self-test capability to insure proper system operation and the selection of alternate modes of operation in the event prime operational modes malfunction or fail. Such built in test equipment increases the overall complexity of the system and must be prevented from inducing prime mission equipment failures. However, such equipment does assist repair personnel in performing the maintenance function.

The efficiency of the maintenance function is also improved by providing handbooks which correctly reflect all the engineering changes to the system and the results of reliability recommendations, such as, preventive maintenance concepts, developed during design reviews or as the result of failure data experience.

Spare equipment reliability is expected to be at least equivalent to prime mission equipment. Therefore, the reliability tasks are expected to be performed on spares. The reliability mathematical model is required to be used as a basis for computing spare

requirements. Similarly, there is a need for close communication between a contractor's engineers woking on prime mission equipment, reliability personnel, and engineers assigned the task of developing or procuring AGE. This need arises not only from the implications of AGE selection based on prime mission equipment configuration but also from the fact that AGE for "L" systems are in themselves usually complex electronic equipments. Obviously, AGE that is not reliable could lengthen, following a prime mission equipment failure, the time that an "L" system is either in a down-state or required to operate in a less accurate and less desirable alternate mode.

Reliability demonstrations and reports are common to MIL-R-27070, MIL-R-27542, and MIL-R-26474.

c. MIL-R-26474, Reliability for Production of C-E Equipment

MIL-R-26474 requires tasks which are essentially similar to those suggested in MIL-R-27070. These tasks are also compatible with work items in MIL-R-27542. Two areas of common concern in these three specifications which have not been discussed are reliability demonstration via equipment testing, as opposed to analytical or mathematical demonstration, and monthly reports to ESD.

ESD recognizes that the basic sequential model presented in MIL-R-26474 is not directly applicable to a complete "L" system which may have several alternate modes and redundant replacements for various functional circuitry. The basic sequential model is viewed as a possible vehicle for reliability demonstrations of simple series systems, a particular mode of operation of a complex system, a subsystem of a system, etc.

ESD requires the submission of a test plan for approval prior to the commencement of any reliability tests. The suggested mathematical model for reliability demonstration is a critical item of a contractor's plan. It governs the duration of the tests and the type and quantity of data or information to be collected and processed. ESD does not consider that a reliability test plan is complete until a clear indication of the contractor's failure feedback system and corrective action loop is presented. The basic loop will have been agreed to at the guidance meetings.

ESD is also concerned over the type of failure analysis (records vs laboratory) to be performed as the result of any reliability test failure. Mere records or data analysis is not considered to be completely satisfactory for the initiation and support of corrective action. Records must be supplemented by laboratory analysis.

Contractor's monthly reliability reports to ESD may be separate items or a section of the contractor's overall monthly reports. ESD expects the following types of reliability information to be included in a monthly report: (1) current reliability status and trend; (2) predicted status by next report period; (3) identification of actual and potential weak-links; (4) corrective action contemplated and taken; (5) predictions of corrective action quantitative effects on system reliability; (6) summary of failure analysis conducted; (7) reliability education lectures presented; (8) summary of design reviews held; and (9) action required by ESD to resolve reliability problems. It is recognized that the type and quantity of information in a report is a function of the scope of the reliability program, and the status of the program during a report period. However, it is expected that prime contractors will discuss each subcontractor's activities separately from their own.

Post Contract Award Reliability Program Monitoring

Each System Program Office (SPO) has per ESD policy at least one engineer with direct responsibility for monitoring negotiated reliability programs. Immediate support for this monitoring function is obtained from the reliability organizations at RADC and from the ESD staff reliability organization.

During the contractor guidance meetings, definite ESD/Contractor monitoring points are established. The meetings are arranged to correspond with significant events within the overall system program plan. The main purposes of the meetings are to: (1) review contractor overall progress on the reliability tasks; (2) participate in design reviews; (3) offer recommendations for improvement of contractor performance; (4) review the reliability requirements and progress toward these requirements; and (5) where necessary, redirect the scope and intent of one or all reliability tasks.

Since contractor's reliability reports to ESD will be reviewed, questions will be raised and answers needed which perhaps cannot wait for formal meetings. Therefore, informal communication in the form of letters, memos, etc. is expected to take place throughout a program.

In addition, if a contractor's performance on the reliability program is considered to be marginal, ESD will request, in addition to the previously scheduled meetings, further conferences.

Acknowledgement

The writers would like to acknowledge the assistance of J. Horowitz, ESD Staff Reliability in the preparation of this paper.

DESIGNING RELIABILITY IN SPACECRAFT SOLAR POWER SUPPLIES

I. Doshay and W. F. Emrich, Space-General Corporation, El Monte, California

17290

SUMMARY

Recently completed studies on proton radiation and meteoroid damage involving solar cells have prompted a fresh look at solar power supplies from a reliability point of view. Considerations of both catastrophic failures and degradation of solar power devices are included. Two design concepts have been prepared, each of which encompasses techniques of redundancy to obtain a high level of reliability. The reliability goal selected for this design is 99% for a lifetime of one year.

A design reliability analysis is made of each of the alternative designs. Reliability techniques are used in deciding between the designs. Sample calculations are included for the effects of redundancy, as well as environmental effects such as radiation and meteorite damage. Tables and graphs are presented covering the effects of radiation and meteorite damage. All sample calculations, tables and graphs presented have been specifically selected to provide an aid to the design engineer for use in the design of solar power supplies.

Introduction

A fundamental necessity in the considerations of a vehicle operating in space is a source of power. For long periods os space operation, it is desirable that this power source be developed from the space environment itself. Three sources, thermal, nuclear, and solar energy are considered to be possible within current technological limitations. Since failure or success of the entire mission in space is dependent on the reliability of the enery conversion system and the source of storage and supply, it is appropriate to perform detailed analyses of such systems prior to determining the configuration for a given application.

The thermal energy power sources appear to have considerable performance and reliability advantages over solar and nuclear energy devices. However, a scarcity of application data exists on such devices beyond their experimental uses. Research into areas of nuclear source power devices has been quite extensive. Practical applications of such equipment are now in production within NASA programs which are identified under the SNAP designation. Studies are now being conducted on the reliability of these space power mediums, and these are intended for future publication releases.

Recently completed studies on proton radiation damage involving solar cells has prompted a fresh look at solar power supplies from a reliability point of view. These new sources of information, together with other readily available information (such as expected meteoroid damage, component failure rates, and an understanding of the expected environment), present a considerably more complete picture for the use of design engineers.[1,2]

This paper is an attempt to compile information from the various solar sources into a logical methodology as an aid to the design engineer. Considerations of both catastrophic failures and degradation of solar power devices will be discussed separately. Failures caused by meteoroid impact severe enough to cause fracture of a cell and an open or short circuit caused by thermal expansion will be considered in the first category. Included in the second category will be the effects of proton radiation.

Since the primary purpose of this paper is to discuss solar arrays, all other components of a solar power supply such as batteries, regulation equipment, etc., will be kept constant, regardless of the solar array configuration. Using this technique, all differences in the system reliability must be attributed to the solar arrays.

The calculations of reliability made in this paper are made with the following assumptions:[3]

1. Open circuits of mounted solar cells occur at random.
2. Shorts to ground within the array do not occur.
3. The probability of a short sircuit of an individual solar cell is negligible. The failure rate in this mode is assumed to be zero.
4. Failure rates of the interconnections are negligible.

Catastrophic Failure Effects

Considerable solar array environmental study by the authors on such projects as Ranger, OSO, Transit, and Arents indicates that, using the present fabrication techniques, thermal expansions are not cause for malfunction problems (independent of the substrate). Considerable damage will occur to filter glasses, but this damage has no apparent effect on the power-producing capability of the solar panel.

Experiments indicate that at meteoroid impact energies above 10^6 ergs, damage to a cell may be sufficient to cause complete failure of the cell. This energy corresponds to a visual magnitude between 18 and 19 (Whipple). Referring to figure 1, we see that impacts of this energy will occur at the rate of 4 per 1000 ft^2 exposed area per hour (worst case).[4, 5, 6, 7] Assuming the area of a solar cell as 2 cm^2, we find that the failure expectancy for a cell is 0.075 per year, or the probability of surviving meteor destruction is

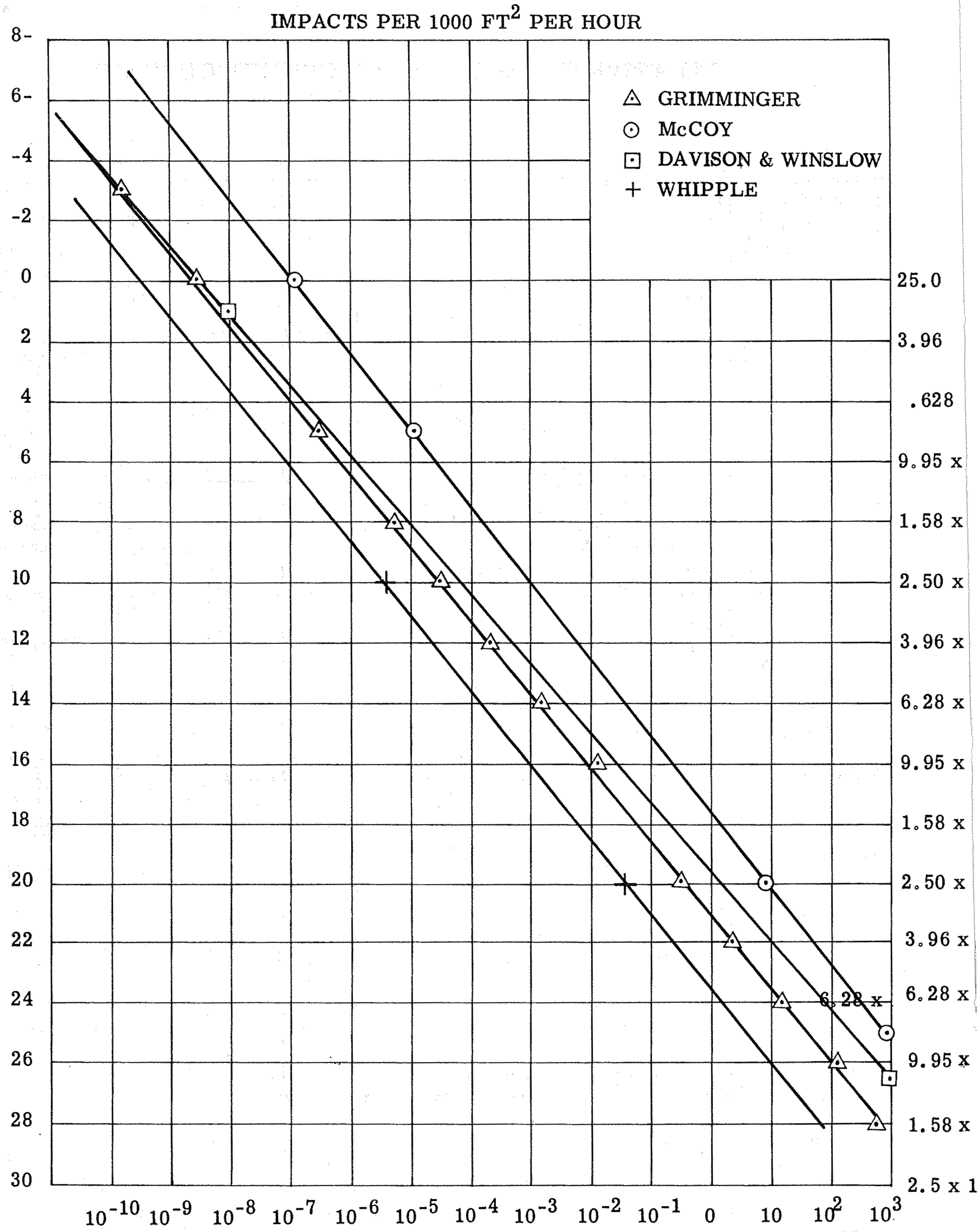


FIGURE 1. Impacts Per Unit Area Per Hour Vs Mass of Meteroid

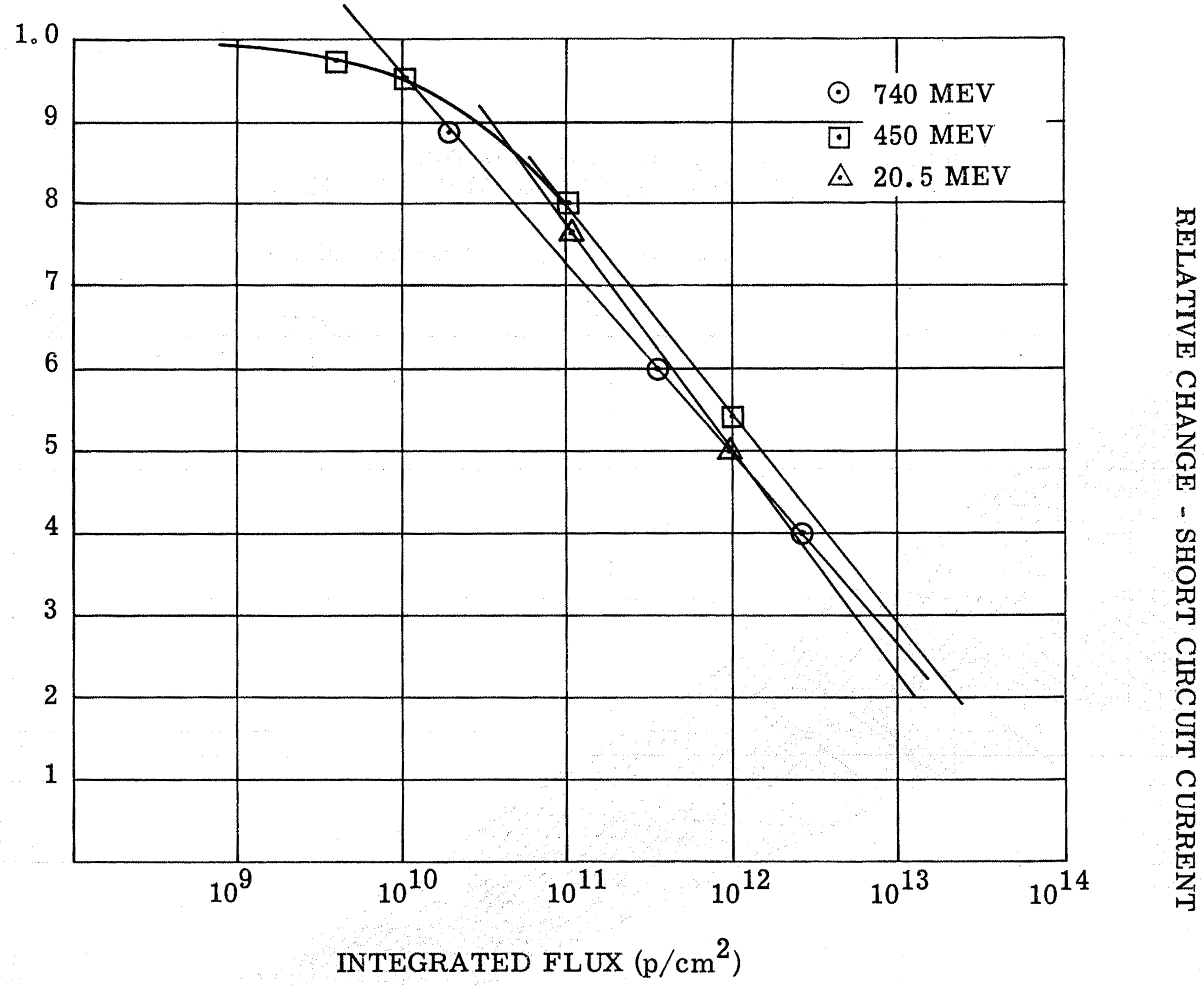


FIGURE 2 Proton Flux Affects on Solar Cell Current Changes

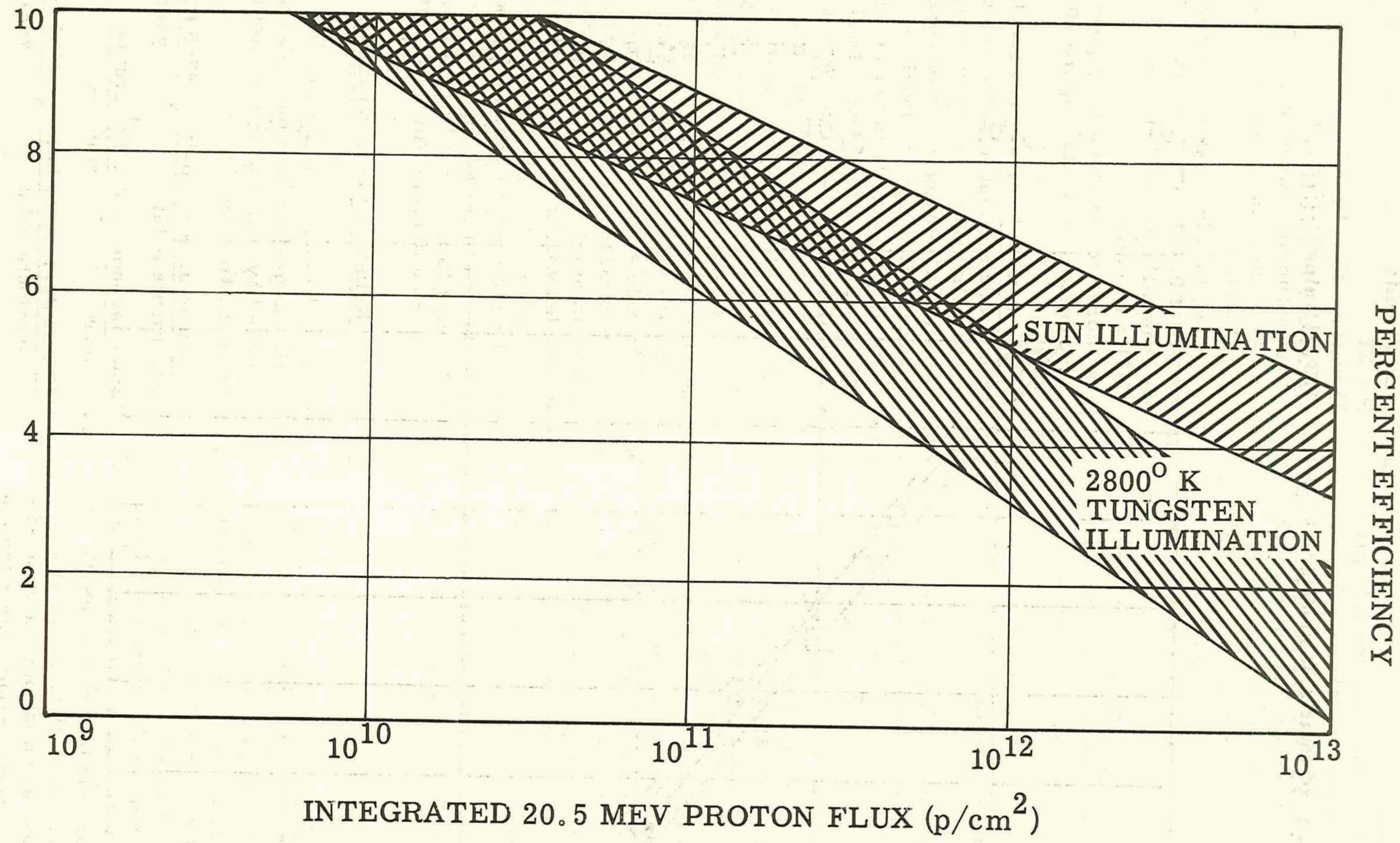


FIGURE 3. Typical Silicon Solar Cell Power Output Degradation During Proton Bombardment

1-0.075 = 0.925 for the single cell in a near-space orbit for one year.

It may be noted that another approach to predicting meteoriod effects may be taken on the basis of the accumulation of total hole area as a function of time.[8] Such approach may be directly related to the thickness of the shield and the material of which it is made. However, it would be difficult to interpret effects of non-hole making meteor collisions into this time-dependent-hole-area methodology. This is believed to be primarily due to the expectancy of failures of cells on the basis of the number of collisions sufficient to cause damage rather than the hole area involved.

Degradation Effects

Recent estimates of proton flux in the Van Allen radiation belts place the flux at 2×10^4 ($E \lesssim 40$ mev) protons/cm^2-sec for the inner belt and 10^2 ($E \lesssim 60$ mev) protons/cm^2-sec for the outer belt.[9, 10, 11]

Studies recently completed by Denney and Downing[1] give us a basis for applying these estimated fluxes. These studies are partially summarized in figures 2 and 3. Figure 2 is a composite showing the degradation as a function of integrated flux for 3 particle energy levels. The very narrow spread of the curves on this figure suggests that damage is not heavily dependent upon the energy involved and gives us a firm foundation for basing our calculations on the basis of integrated flux without regard to the energy of the protons.

Figure 3 shows the typical power output expressed in percent efficiency as a function of integrated flux.

Sample Problem

As an example of how to apply this information, we will assume a hypothetical orbit. This satellite will be in a 100-minute orbit; 60 minutes in sunlight, 40 minutes in the earth's shadow. Ten minutes of each orbit will be in the inner Van Allen belt, and 10 minutes will be in the outer belt. Power requirements will be assumed to be 50 watts continuous, with a 10 minute peak of 60 watts each orbit. Our reliability goal is 99% (solar arrays only) with a lifetime of one year.

Based on the above assumptions, it is determined that the average power requirement for the satellite is 51 watts per hour or 85 watt hours total per 100 minute orbit. Since this amount of power must be generated in 60 minutes out of each 100-minute orbit, the solar array must be capable of producing 85 watts of power.

Let us further assume that we desire this power at 28 volts.

$P = EI$

85 watts = 28 volts x I

I = 3.06 amps

Assume an optimum voltage of 0.467 v per cell. The number of cells in series to get 28 v is equal to 28/0.467 = 60 cells.

Using 11% efficiency gridded cells, the average current of 0.467 volts is 51 ma. The number of cells in parallel to get 3.06 amps is equal to 3.06/.051 = 60 cells.

Therefore, to get 85 watts of power under the above circumstances would require 60 x 60 = 3600 cells.

We will examine two electro-mechanical configurations, and attempt to define the better one in terms of reliability. The first configuration which we will call design "A" will consist of 5 individual cells in a series module arrangement (see figure 4). Five cells in series will give 5 x 0.467 v = 2.335 v at 51 ma. Twelve of these modules will be wired in series to get 28 volts (12 x 2.335 = 28). We shall call this series string of 5 x 12 = 60 cells a "bank". Sixty such banks will be required in parallel to get 3.06 amps (60 x .51 = 3.06). Figure 5 shows a sample wiring diagram for design "A". Design "B" will consist of 10 cells which will be sweated to a thin kovar substrate as shown in figure 6. They will be wired in parallel. Ten cells in parallel will give (10 x 0.51 amps) 0.51 amps at 0.467 v and 60 of these modules will be wired in series to give 28 volts (60 x .467 = 28). This parallel-series group of 600 cells (10 x 60) is called a "bank". Six such banks connected in parallel will be necessary to get 3.06 amps (6 x .51 = 3.06). Figure 7 shows a sample wiring diagram for design "B".

Reliability Determination

During the course of a year, the integrated proton flux impinging upon our solar arrays may be calculated by multiplying the total time of exposure by the flux density or

$$\frac{\text{10 minutes, inner belt}}{\text{100 minute orbit}} \times \frac{\text{8760 hours}}{\text{year}} \times \frac{\text{3600 seconds}}{\text{hour}} \times \frac{2 \times 10^4 \text{ protons}}{\text{cm}^2 \text{ sec}} + \frac{\text{10 minutes, outer belt}}{\text{100 minute orbit}} \times \frac{\text{8760 hours}}{\text{year}} \times \frac{\text{3600 seconds}}{\text{hour}} \times \frac{10^2 \text{ protons}}{\text{cm}^2 \text{ sec}} =$$

6.4×10^{10} Protons/cm^2 for the intended mission (one year)

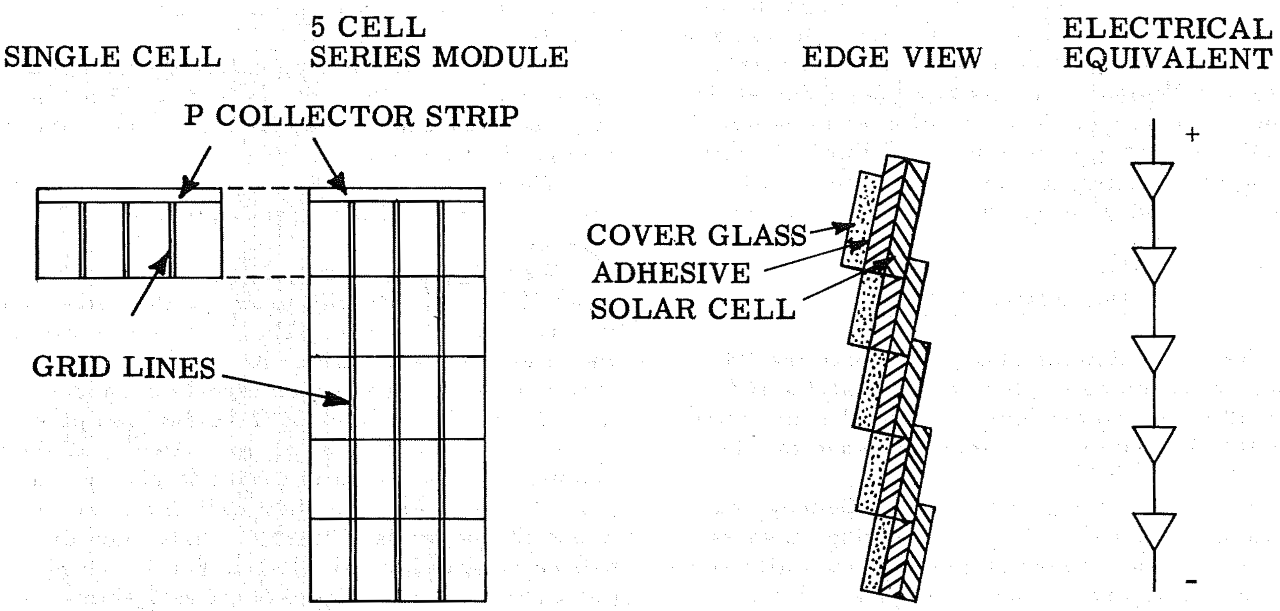


FIGURE 4. Description of Solar Cell Modules

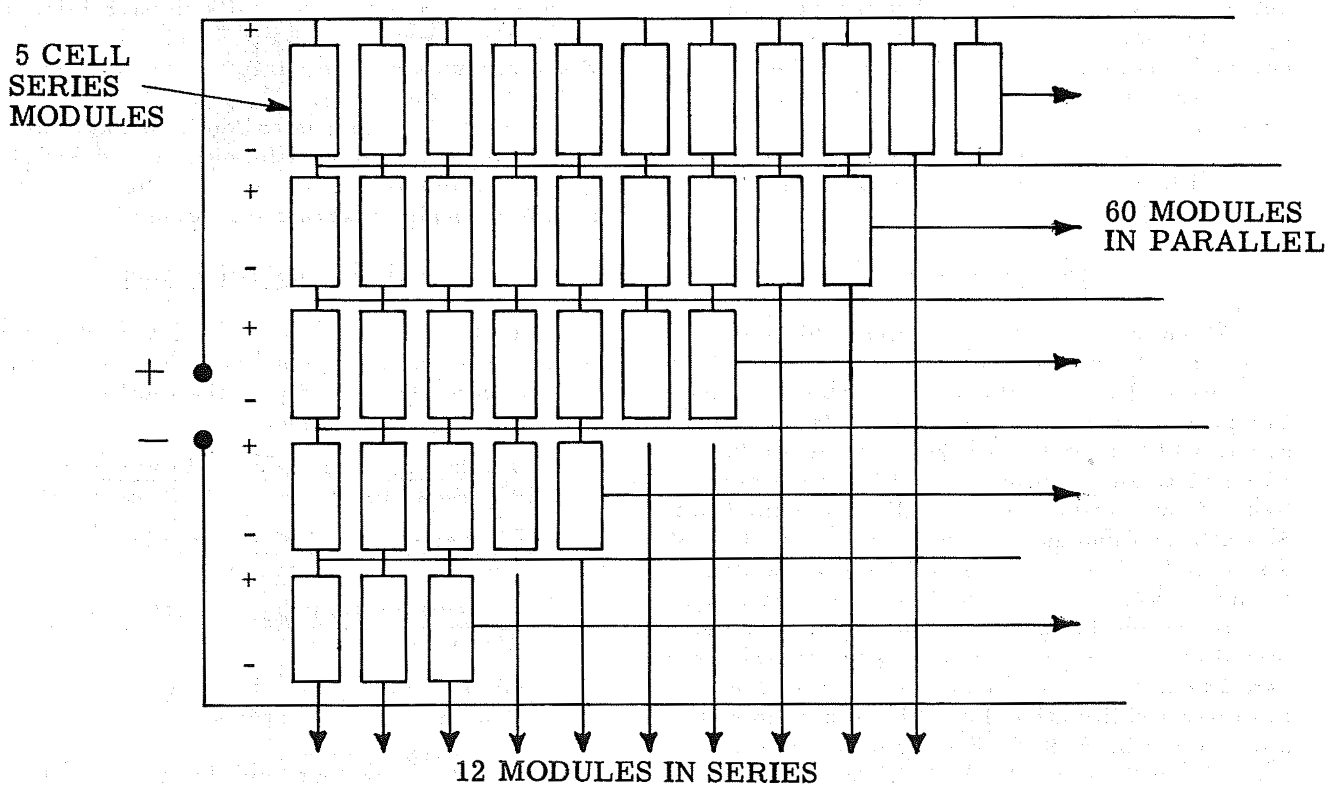


FIGURE 5. Wiring of 5 Cell Series Modules

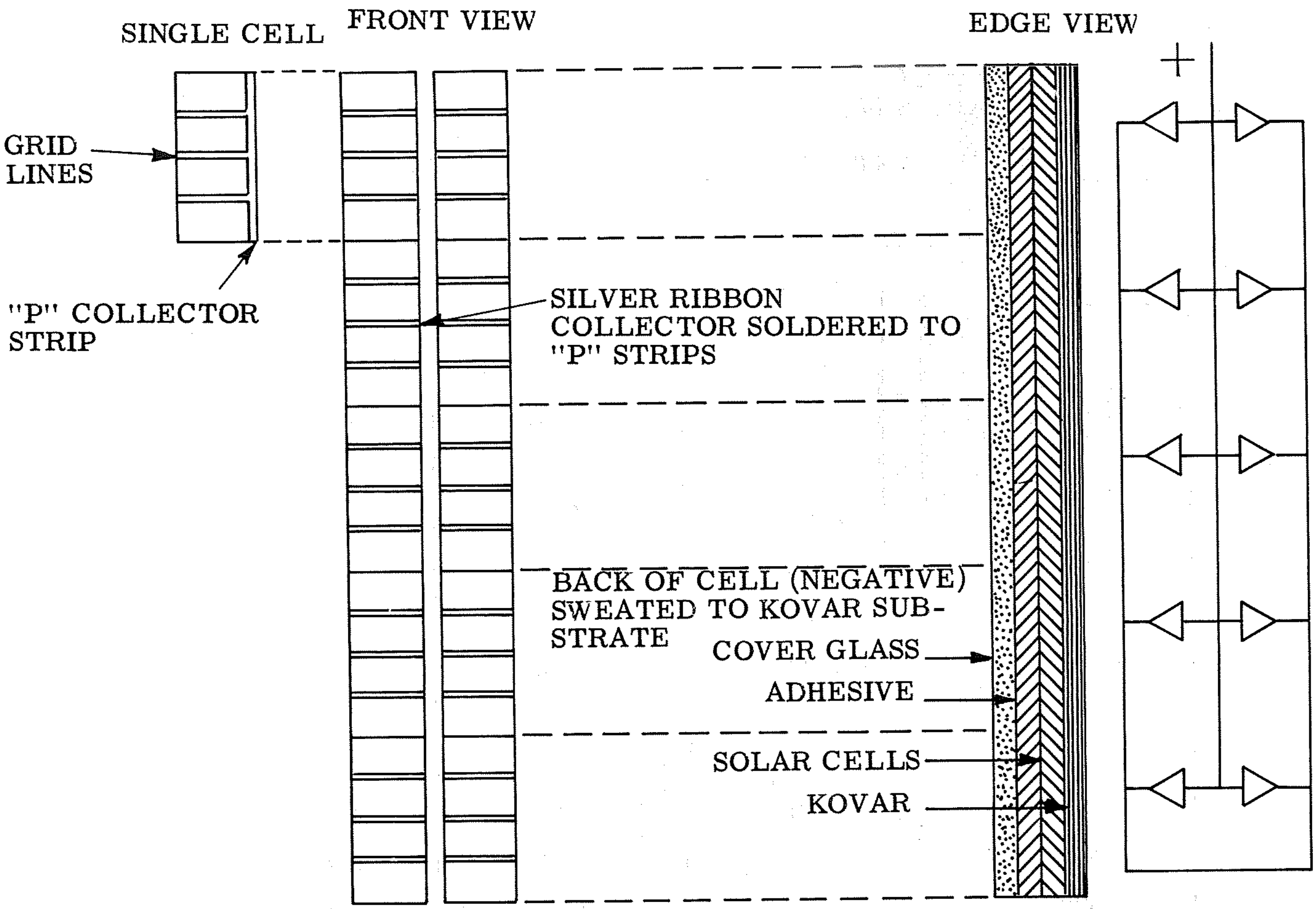


FIGURE 6. 10 Cell Parallel Module

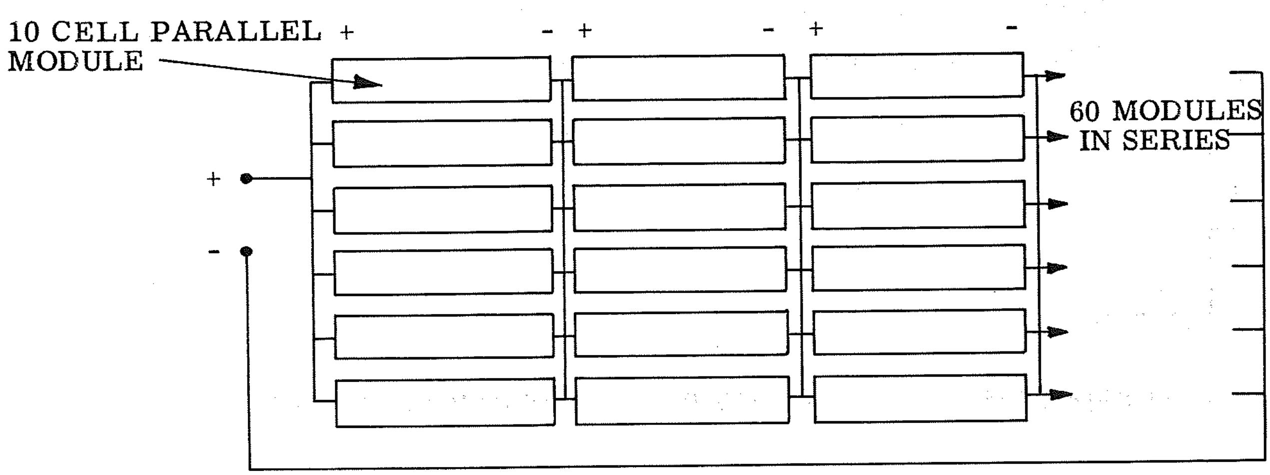
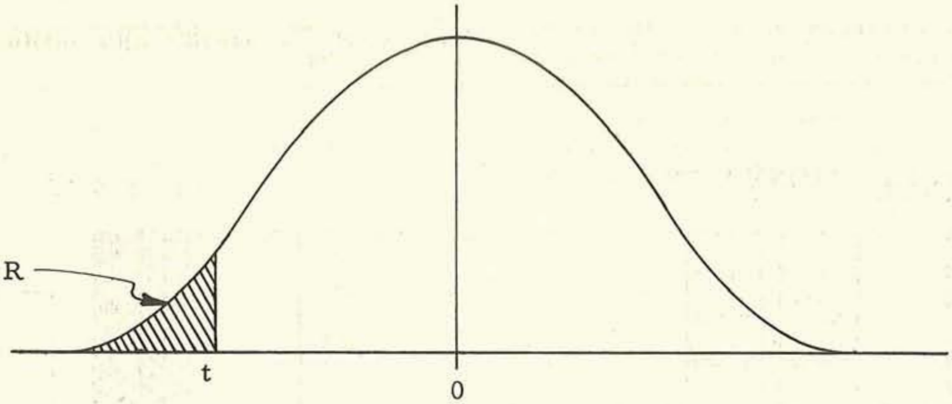


FIGURE 7. Wiring of 10 Cells Parallel Modules



R	t		
.0001	-3.719	.500	0.000
.0005	-3.291	.550	.126
.001	-3.090	.600	.253
.005	-2.576	.650	.385
.010	-2.326	.700	.524
.025	-1.960	.750	.674
.050	-1.645	.800	.842
.100	-1.282	.850	1.036
.150	-1.036	.900	1.282
.200	- .842	.950	1.645
.250	- .674	.975	1.960
.300	- .524	.990	2.326
.350	- .385	.995	2.576
.400	- .253	.999	3.090
.450	- .126	.9995	3.291
.500	0.000	.9999	3.719

TABLE 1

NORMAL DISTRIBUTION - SELECTED PROBABILITY POINTS

Referring again to figure 3, we see that at an integrated dose of 6.4×10^{10} protons/cm^2 we can expect to lose, in the worst case, 18% of the initial power-producing capability of the cells.

Results of independent calculations shown below are in agreement with the above calculations:

$$\sigma = \sqrt{N_{pq}} = \sqrt{(878 + X)(0.323)(0.667)}$$

$t_{99} = 2.326$ (from Table 1)

Model	Integrated flux	Fraction of Initial Max. Power
Freden and White, normalized to Van Allen's 2×10^4 P/cm^2/sec at peak and extended to 20 mev	10^{11} P/cm^2 for E=20 mev	75%
Freden and White spectrum above 40 mev normalized to Van Allen's 2×10^4 P/cm^2/sec at peak; extensions to 20 mev using Haugle and Kuffen Slope.	10^{12}P/cm^2	55%

Discussing first design "A" (5 cells in series), the calculations of radiation damage indicate an 18% loss of power. Therefore, we must plan for an 18% excess of cells at the start of the mission. Since 3600 cells will give the required power at the onset:

$X - .18\,x = 3600$

$= 4390$ cells or 878 each 5 cell modules will provide sufficient power including offset of the radiation damage.

Since the probability of surviving meteor destruction of a cell as previously estimated is 0.925, the probability of survival of a 5 cell series module is $(0.925)^5$ or 0.677, and the failure expectancy equals 1 - 0.677 or 0.323 for the intended one-year mission. Applying this failure expectancy to the number of modules which we must provide to satisfy the radiation hazard, we find that we must carry

$$X = (878)(0.323)+(878)(0.323)^2+(828)(323)^3+ (828)(323)^4 + \cdots = \frac{a}{1-r}$$

X = 419 extra modules in our solar array because of anticipated meteorite damage. But 419 extra modules is the average number we can expect to lose. Half of the time we can expect to lose less than 419 modules and half the time more than 419 modules. The problem then becomes one of determining that number of extra modules such that at the end of a year in orbit we can expect a minimum of 878 good modules, 99% of the time.

Since N is large, the normal approximation of the binomial will be used where

X = Spare cells for 99% reliability
N = Total cells required = 878 + X
P = Module failure expectancy = 0.323
$q = (1-p) = 0.677$ = probability of survival
$\mu = N_p = (0.323)(878+X)$

From the relationship $t = \frac{x-\mu}{\sigma}$, substituting

$$2.326 = \frac{X - (0.323)(878 + X)}{\sqrt{(878 + X)(0.323)(0.667)}}$$

and solving for X using the quadratic formula we find X = 467 modules.

Therefore, in order to satisfy a 99% reliability for the mission for design "A", we must carry 878 + 467 = 1345 modules or 6725 cells.

A similar methodology can be applied for design "B" (10 cell parallel module). In this case, since the individual cells are in parallel and a meteorite hit will remove only 1 cell from the circuit rather than 5 as in the "A" configuration, the calculation will be made on the basis of individual cells (rounded up to groups of 10 cells since the basic building block of this design is a 10 cell module). Total number of cells needed to allow for radiation damage = 4390. Predicted number of meteorite-destroyed cells = 356. Number of extra cells needed to satisfy the 99% reliability requirements = 401, rounded to 410. Total number of cells needed for design "B" = 4800.

Conclusions

As can be seen from the above calculations there are some major differences between the alternative designs. Design "A" requires 1925 or 40% more cells than design "B". Design "A" would also require approximately 29% more area. Therefore, design "B" would be preferred.

The sample problem discussed above was for demonstrative purposes only. No attempt was made to select a "real" orbit. Figure 3 and Table 1 are included at the end of this paper as an aid

to the designers. Once suitable orbits are calculated it should be possible to predict the inherent design reliability of a given solar array.

Bibliography

1. Denny, J.M. and Downing R.G., "Charged Particle Radiation Damage in Semiconductors, I: Experimental Proton Irradiation of Solar Cells" Space Technology Laboratories, Inc., Report No. 8987-0001-RU-000, Sept. 1961.

2. Doshay, I., "Reliability Design for an Orbiting Spacecraft," Aerojet-General report No. S60-232, presented at 1st Seminar on Reliability in Space Vehicles, 5 Dec. 1960.

3. Klein, W.A. and Lehr, S.N., "Reliability of Solar Arrays," presented to Second Annual Seminar of Reliability in Space Vehicles, Los Angeles Section, I.R.E., 5 Dec. 1961.

4. Whipple, F.L., "Meteoritic Material in Space," Chap. 3, Proceedings of the Second International Symposium on Physics and Medicine of the Atmosphere and Space, Nov. 1959, edited by O. Benson Jr. and H. Strughold, John Wiley and Sons, Inc.

5. Grimminger, G., "Probability that a Meteorite Will Hit or Penetrate a Body Situated in the Vicinity of the Earth," Rand Paper P-18, April 1948.

6. McCoy, T.M., "Hyperenvironmental Simulation, Part 1: Definition and Effects of Space Vehicle Environment, Natural and Induced," WADD Technical Report 60-785, January 1961.

7. Davison, E.H. and Winslow, P.C. Jr., "Space Debris Hazard Evaluation," NASA Technical Note D1105, December 1961.

8. Edmiston, R.M., "The Prediction of Meteorite Hole Area in a Space Vehicle Near the Earth," IAS paper 62-29, IAS 30th Annual Meeting, New York, Jan. 1962.

9. Doshay, I., "Spacecraft Environmental Tables and Graphs," Report No. 1974, Aerojet-General Corp., Azusa, California, March 1961.

10. Van Allen, J.A. "Corpuscular Radiations in Space" Radiation Research, 14:540-550, 1961.

11. Hess, R.E. and Badertscher, R.F., "Space Radiation as an Environmental Constituent," RIEC Memorandum 19, Battelle Memorial Institute, January 1960.

ACHIEVEMENT OF RELIABILITY IN SPACE SYSTEMS

Harvey W. Fritz
Space Systems Division
Air Force Systems Command
Los Angeles 45, Calif

The first DOD sponsored Joint Military-Industry Reliability Symposium was held in 1954. During that symposium and the subsequent five symposia, a tremendous number of ideas and techniques related to the improvement of guided missile reliability were presented. Yet, at the close of the last symposium which was held in February 1960, it was the general consensus of opinion that we had a long way to go in achieving the desired level of guided missile reliability.

Recognition of this problem of missile reliability is universal, but consider further the fact that in the past few years the United States has embarked upon a full scale space program. This program currently consists of the development of such systems as: manned lunar exploration vehicles, communications and weather satellites, and military space systems.

In the development of space systems the designer is confronted with reliability problems which make those which face the missile designer seem simple by comparison. He must now design systems which will function continuously for long periods of time without maintenance in new kinds of environments, such as: a near perfect vacuum, radiation, zero gravity, meteorite and micrometeorite impact, and new temperature considerations. These environments are, in addition to the shock, acceleration, vibration and temperature environments which are inherent in the boost phase.

Table I presents some relative reliability requirements for a subsystem in aircraft, missile, and satellite applications. The typical subsystem chosen is a 25 Watt UHF transmitter which might be used in any one of the three applications. The mission times and reliability requirements shown in Table I have been taken from documents containing requirements which have been placed on existing systems and are therefore considered representative of actual requirements. It should be noted that although the Mean Time to Failure (MTTF) for the transmitter in a missile application is only slightly higher than the MTTF in an aircraft application, the MTTF requirements for the space application are several orders of magnitude more severe than those requirements for either missile or aircraft applications.

The magnitude of the design problem created by the high vacuum environment of space is exemplified in the following quotation from a Hughes Aircraft Company Technical Memorandum (Reference 3):

"One of the most severe problems presented by the space environment is the effects of ultra-high vacuum on lubricants and metallic surfaces. Most lubricants which are presently available are useless in space due to their high vapor pressure which eventually results in their complete volatilization. When the lubricant has disappeared, the coefficient of friction of the surfaces in contact increases greatly.

"The loss of lubricant is followed by a progressive loss of surface films either by volatilization or as a result of frictional wear. Once surface films and adsorbed gases are lost, contact between the uncontaminated surfaces can result in galling and seizing or 'cold welding.'

"The problem of preventing seizure requires consideration not only in bearings, but also in electrical contacts, such as, commutator brushes, slip rings, switches and relays."

This same reference describes an experiment which demonstrated "cold welding" of materials in high vacuum. In this experiment a cold rolled steel plate and rod were brought in contact with each other in a vacuum of 8×10^{-9} mm Hg after elimination of surface contamination. After contact, the rod was moved across the surface of the base. Complete seizure occurred after a short distance of movement. A measurement of the tensile strength of the seizure was made and was found to be approximately 45,000 psi, which approaches the bulk strength of the metal. It should be noted that the vacuum used in this experiment is one which would be experienced at approximately 350 miles above the earth's surface. It is estimated that the vacuum in space can become 10^{-14} mm Hg or lower.

Other effects of high vacuum on materials are sublimation and evaporation of materials. Certain materials may give off corrosive gases when they sublime or evaporate. Such corrosive gases may cause severe corrosion effects in adjacent equipment or may substantially alter the strength or functional characteristics of the component containing the sublimating or evaporating material.

The penetrating radiation environment of space may be a formidable problem to the designer of space vehicles. Penetrating radiation may be due to a variety of sources. Probably the most important sources are: Cosmic radiation, trapped radiation (Van Allen Radiation), and solar-flare radiation. Materials subjected to radiation from these sources may severely change in their physical and chemical properties. As a result, components containing these materials may suffer intolerable changes in their performance characteristics or strengths.

High temperatures within a space vehicle will be caused primarily by direct solar radiation, although other effects such as earth shine, earth radiation, and internal heating of the equipment itself will contribute to the high

temperature environment. Normally, when designing for temperature control, the engineer considers the effects of convection in dissipating heat. However, he must keep in mind that there is no convection in space. One can design for temperature control by means of absorptive and reflective surfaces on the outside protective skin of the space vehicle. By adjusting the reflective and absorptive properties of the surfaces, the intake and output of heat can be adjusted; and if it is balanced with the amount of heat being generated by the internal equipment, then the internal temperature can be made to stabilize at an acceptable level. The effect of direct solar radiation is on the side of the space vehicle which is toward the sun. This side may become very hot, while the side away from the sun may be very cold. This condition may be minimized by rotation of the vehicle. However, this may not be feasible in the case of a vehicle in which parts of the vehicle must be continually oriented toward the sun.

Collision with space particles such as meteorites and micrometeorites are a definite space problem and must be taken into account in design. A considerable amount of data has been obtained relative to the density of the space dust micrometeorites, their masses, and their sizes. Table II gives some design figures which can be used for determining the thickness of the protective shell to be used on the outside of a satellite or space vehicle. Another problem created by space dust is that after a period of time the outside surface will become roughened as if it were sandblasted. This sandblasting upsets the balance between absorptivity and reflectivity in the case of those space vehicles which are using this means as a device for temperature control.

The reliability problem of space systems is further complicated by their tremendous critical part complexity. In a missile or space system there are hundreds of thousands of critical parts. Publications indicate that the Atlas missile contains between 250,000 and 300,000 parts, the majority of which are critical.

Now consider the potential complexity of a manned space system. The number of critical parts may be a million or more. If a failure of a part occurs in a space system after launch, you have to live with the consequences. There just isn't any repair. The consequences of failure of such parts as relays, connectors, transistors, etc., may be the loss of a multi-million dollar missile, the failure of a multi-billion dollar attempt to land a man on the moon and return him safely, or may jeopardize our national prestige or security.

It is significant to note that there are a number of publications which indicate great concern by the Department of Defense relative to the unreliability of electronic equipment, both ground and airborne. Much of this concern was developed during World War II. Since that time improvements have been made in electronic part and equipment reliability. However, the increase in critical part complexity of our space systems has been increasing at a greater rate than the part improvement rate.

Now the question arises: How much reliability is required for the critical parts of space systems? In order to answer this question, it is necessary to examine the relationship between complexity and reliability.

Reliability is defined as the probability that a system will perform a required function under specified conditions without failure.

Mathematics of probability states that the overall reliability equals the product of the reliabilities of the individual parts as follows:

$$P_{overall} = p_1 \,.\, p_2 \,.\, p_3 \,.....\, p_n$$

where p_1, p_2, p_3, p_n are the reliabilities of each of the individual parts of the system. A part is defined as one piece, or a combination of pieces joined together which are not normally subject to disassembly without destruction of the designed use. In this formula it is assumed that the failure of any one of the parts will cause a failure of the system. The graph in Figure 1 illustrates the effect of complexity on reliability for systems of various complexities. It can readily be seen that in order to achieve a reliability of 80 percent in a system having 400 parts, each part must have a failure rate no greater than 1 per 1800 or a reliability of 99.945%. Now consider the reliability required for each of the parts of a 100,000 part system in order to achieve an 80% system reliability. The answer is 99.99978% or 1 permissible failure per 450,000.

If this answer startles you, it should be noted that the failure rate should really be much less, because the probabilities of undetectable human errors throughout the chain of events from the time of system conception to the time of "end use" were not included.

The foregoing treatment of reliability versus complexity indicates two areas in which to concentrate in order to achieve high orders of reliability. These are: first, simplification and second, increased critical part reliability. Simplification should certainly be attempted to the maximum. However, due to the ever increasing demands for increased performance and for the accomplishment of increasing numbers of exotic tasks, the complexity of our aerospace systems continually increases. Therefore, it appears that achievement of an ultra high order of reliability for parts, components, and subsystems is the approach which must be pursued.

At this point I am sure you are beginning to think that the task of achievement of the required ultra high level of reliability is impossible. It is not impossible. However, its accomplishment is a challenge of a staggering magnitude to the imagination of our industrial management and to the ingenuity of our design, production, test, and quality control engineers, and our scientists.

Fundamental to the accomplishment of the task is an immediate expansion of management disciplines to control the actions of every individual, who could conceivably degrade the

system reliability, from the time of conception through "end use" in order to assure that the actions of these individuals are realistically directed toward attainment of the reliability goal.

Much can be said about the disciplines required in each major management area. However, I wish to address my comments to the design area, because I believe it is the designer who has the greatest impact on the level of reliability finally achieved. It is the efforts of the designer that establish the highest potential reliability of a system. Reliability must be designed into the parts, components, subsystem and systems--it cannot be tested or inspected in.

In order for a designer to achieve the ultra high degree of reliability required in aerospace systems he must meticulously pursue the following basic tasks:

1. Acquire or determine the level of environmental stresses to which his equipment will be subjected.
2. Design his equipment to be compatible with established environmental stress levels.
3. Prove design adequacy.

Knowledge of the environmental stresses to which an equipment will be subjected is the basic building block for a designer. He must know every conceivable environment and its magnitude both external and self induced to which his equipment will be subjected throughout its entire life cycle. Where a firm knowledge of the environmental conditions is not available a conservative estimate must be established.

After establishment of the values of environmental stresses to be used, the designer must consider the following major factors in order to achieve a reliable design:

1. Safety factors and safety margins.
2. Failure mode identification and cause.
3. Failure effective analysis.
4. Standardization of design and parts.
5. Simplification of design.
6. Assessment of state-of-the-art.
7. Trade-offs of parameters.
8. Derating of parts.
9. Redundancy for greater reliability.
10. Maintainability.
11. Producibility.
12. Design for acceptable storage life with minimum packaging or need for special environmentally controlled storage.
13. Ease of operation.
14. Ease of transportation.
15. Ease of inspection.
16. Human engineering.
17. Calibration.

Throughout the design process the designer is faced with the problem of determining whether or not he has designed the required degree of reliability into a part, component, subsystem or system. It is common practice for designers to rely on the following sources for this evaluation:

1. Testing one or a small number of parts or equipments to specific environmental levels.
2. Analysis of field and factory failure data.
3. Analysis of flight results from telemetry records.

Environmental testing of an equipment is certainly a necessary part of the design evaluation procedure. However, testing one or a small number of equipments to a specific environmental level raises a serious question relative to the degree of confidence that the strength of the equipment is not at or close to the threshold of failure. If, in fact, the equipment were at the threshold of failure, a great probability exists that subsequently procured equipments of the design which was tested would fail below that specified environmental level due to manufacturing variability. It is also significant to note that accurate environmental stress levels are rarely ever known early in a developmental program. Hence, the designer could be testing to a value of an environmental stress level below that which will actually be encountered. This possibility in combination with inevitable manufacturing variability could result in high probability of subsequent failure of his equipment.

Analysis of field failure data is very important in proving design adequacy. However, the conditions surrounding the acquisition of these data, e.g., pressure of schedules, training of personnel, etc., can seriously affect their accuracy and completeness. Furthermore, the environmental conditions in which these failures occur are distinctly different than aerospace system flight environments. As a result, a great deal of speculation relative to the exact cause of failure is inherent in this method of evaluation of design adequacy.

There certainly is no substitute for flight test programs for demonstrating the performance capability of an aerospace system. However, it is certainly a fallacy to depend primarily on telemetry from a system during flight to pinpoint accurately the cause of a failure. To obtain enough channels of telemetering to accomplish failure analysis in a system having hundreds of thousands of critical parts is practically impossible.

This method of evaluation definitely had serious limitations when applied to aerospace systems where the launched systems cost millions of dollars. Furthermore, in most of our space programs the total number of vehicles to be launched is very small, or it may even be one.

Therefore, the highest possible degree of confidence that a reliable design has been achieved must be developed prior to launch.

I believe that one of the most realistic methods of proving design adequacy with the highest degree of confidence is through the engineering principle of the safety factor or safety margin.

The principle of the safety factor is not new. It has been used for ages by engineers primarily in the design of structures and devices which involve human safety, i.e., building structural

members, bridges, elevators, etc. We look upon the aircraft as a highly reliable machine. This high degree of reliability is primarily due to the establishment of safety factors in the strength of critical parts, such as wings, landing gears, control mechanisms, etc. It is very important to note that the use of safety factors is not something that is optional on the part of the designer of aircraft critical parts--it is a design discipline which is rigidly imposed on the designer through specifications.

The safety factor is defined as the ratio of the ultimate strength of an equipment to the maximum stress to which the equipment will be subjected. In order to prove the existence of a safety factor it is necessary to subject an equipment to a "test-to-failure." Test-to-failure is accomplished by subjecting the sample to increasing levels of an environmental stress until failure occurs--failure may be either functional or structural. Generally, when a designer has proven that he has designed the specified safety factor into an equipment, he is not required to repeat the test. The question then arises: Would testing of additional samples of the same equipment produce the same value of a safety factor? Due to inevitable manufacturing variability, a variation in the equipment strength and the value of the safety factor can most certainly be expected. Since this is true, it is necessary to determine the magnitude of these strength variations, because the existence of a large variation could result in a high probability of failure.

Considering the fact that the failure rate of the critical parts of our aerospace systems may be only one permissible failure in 500,000 or 1,000,000, knowledge of the strength for these parts and its relation to the maximum environmental stresses to be encountered is absolutely necessary.

In order to determine the variation in the strength of a part or equipment it is necessary to "test-to-failure" samples of the parts or equipments. The results of these tests-to-failure can be plotted as shown in Fig. 2.

The standard deviation of the resulting variation about the average strength can then be calculated (See Appendix for a sample calculation). The number of standard deviations that exist between the maximum environmental stress and the average strength can then be referred to as the "safety margin." The utilization of the "safety margin" evaluation technique provides the designer with a realistic means of assessing the probability of a failure due to strength variations.

It is important to note that a test-to-failure reveals modes of failure and critical weaknesses. Therefore, after each test-to-failure the character of the exposed modes of failure and critical weaknesses should be thoroughly analyzed. Such an analysis after the first test may indicate that a very simple design change could increase the strength of a part or equipment substantially. As a result of incorporating the change, the second test might demonstrate a safety factor so large that no further testing would be necessary. Even though a second sample were not available for test-to-failure, an increase in confidence in the design would be established as a result of the design change. Another result of the mode of failure analysis might indicate that the part or equipment is totally unacceptable.

If several parts or equipments are tested to failure and the resulting safety margin is unacceptable, the designer may increase the safety margin in the following ways: The first solution is to reduce the strength variation. This might be accomplished, for example, by a more rigid quality control. The second solution is to increase the average strength through redesign. The third solution is to reduce the maximum environmental stress. An example of how this could be accomplished would be the provision of additional cooling in a case where heat is the problem. Another example would be the isolation of the part or equipment from the hostile environment, e.g., isolation of parts or equipments from the effects of a "hard vacuum" by placing them in a pressurized hermetically sealed container.

Now the question arises: What value of safety margin should be demonstrated for the critical parts of a space system? Since failure rates of one in 500,000 or 1,000,000 may be required, the answer should be at least 5 standard deviations.

Since the safety margin forms the basis for an estimate of a failure rate, the inevitable question arises: How much confidence can be assigned to the values of safety margins obtained from testing-to-failure small numbers of units, such as 10 or 12? In a statistical sense, the answer is: Very little confidence when evaluating the critical parts of equipments of highly complex space systems. The number of units of hardware available for test-to-failure, even including parts, is definitely too small to develop a reasonable degree of statistical confidence. This fact can be appreciated when one considers the fact that demonstration of a failure rate of one in 100,000 at a 90 percent confidence level requires 230,259 units to be tested before first failure - even at a 50 percent confidence level, 69,315 would have to be tested before first failure.

Even though the estimate of the failure rate on the basis of the demonstrated safety margin may be crude, nevertheless, it provides the basis for engineering confidence not attainable by any other means.

Now, I wish to present an actual example of an application of the safety margin method of proving design adequacy. The example chosen was taken from the document in Reference 2, and involved the design evaluation of a gas producing squib. Figure 3 shows a plot of the data acquired during the evaluation, and the following quotation provides the explanation of evaluation procedure and results quoted below:

"In order to arrive at an engineering confidence level in the squib, a determination was made of the degree of performance variability. Moderate sample sizes were tested and the results plotted as shown in Figure Number 5

(Fig. 3 in this text). This data was then analyzed and conclusion reached in regard to the safety factor existing between the actual performance and the requirement.

"The group on the left represents a control group which was tested at room ambient temperature with no previous environmental testing. The center group represents items that underwent 20 cycles of thermal shock between -80°F and +220°F. The group on the right represents items that underwent 20 cycles of thermal shock, identical to the previous group, but which in addition were subjected to shock and vibration environments at 220°F. The ordinate represents gas volume expressed in cubic centimeters. As indicated, 600 cc is the medium activation volume required.

"Results of the control group around a mean of 980 cc indicates a rather wide variability.

"The Thermal Shock group shows a much narrower variability around approximately the same mean.

"The combined Thermal Shock and Dynamic Test Group shows approximately the same degree of variability as the previous group but at a higher mean of approximately 1060 cc.

"However, the large number of sigma units between the mean and the requirement in every group indicates that there is practically no probability of any of these squibs failing to deliver the minimum 600 cc volume required.

"During the development of the squib, the mean gas volume has steadily increased up to the present level shown at the right with a corresponding decrease in variability. The present squib with its extremely low variability is regarded as a high reliable battery component."

In this presentation I have attempted to point out only the fundamental aspects of the safety factor and safety margin concept for proving design adequacy. A more detailed treatment may be acquired through a study of the documents in attached list of references.

In summary, I wish to state again that it is the designer who established the highest potential reliability which may be attained by a system. Therefore, it is incumbent upon the designer to use the most effective tools available to prove adequacy of his designs. It is my firm conviction that the widespread use of the safety factor and safety margin concept will significantly accelerate the achievement of the high degree of reliability required in our space systems.

REFERENCES

1. Lusser, Robert: Reliability Through Safety Margins, Army Rocket and Guided Missile Agency, Redstone Arsenal, Alabama, October 1958.

2. McCutcheon, Robert: Reliability Programs, U.S. Army Signal Research and Engineering Lab., Fort Monmouth, N.J.

3. Seizure of Metallic Surfaces in Ultrahigh Vacuum; Report No. TM-685, Hughes Aircraft Co., 15 July 1961; E.E. Brueschke and R.H. Suess.

4. Designer's Guide to Space Radiation Effects; Lockheed Missiles and Space Division, Lockheed Aircraft Corp.; Document No. LMSC 5-10-61-29.

TABLE I

Typical Reliability Requirements for Electronic Subsystem
(25 Watt UHF Transmitter)

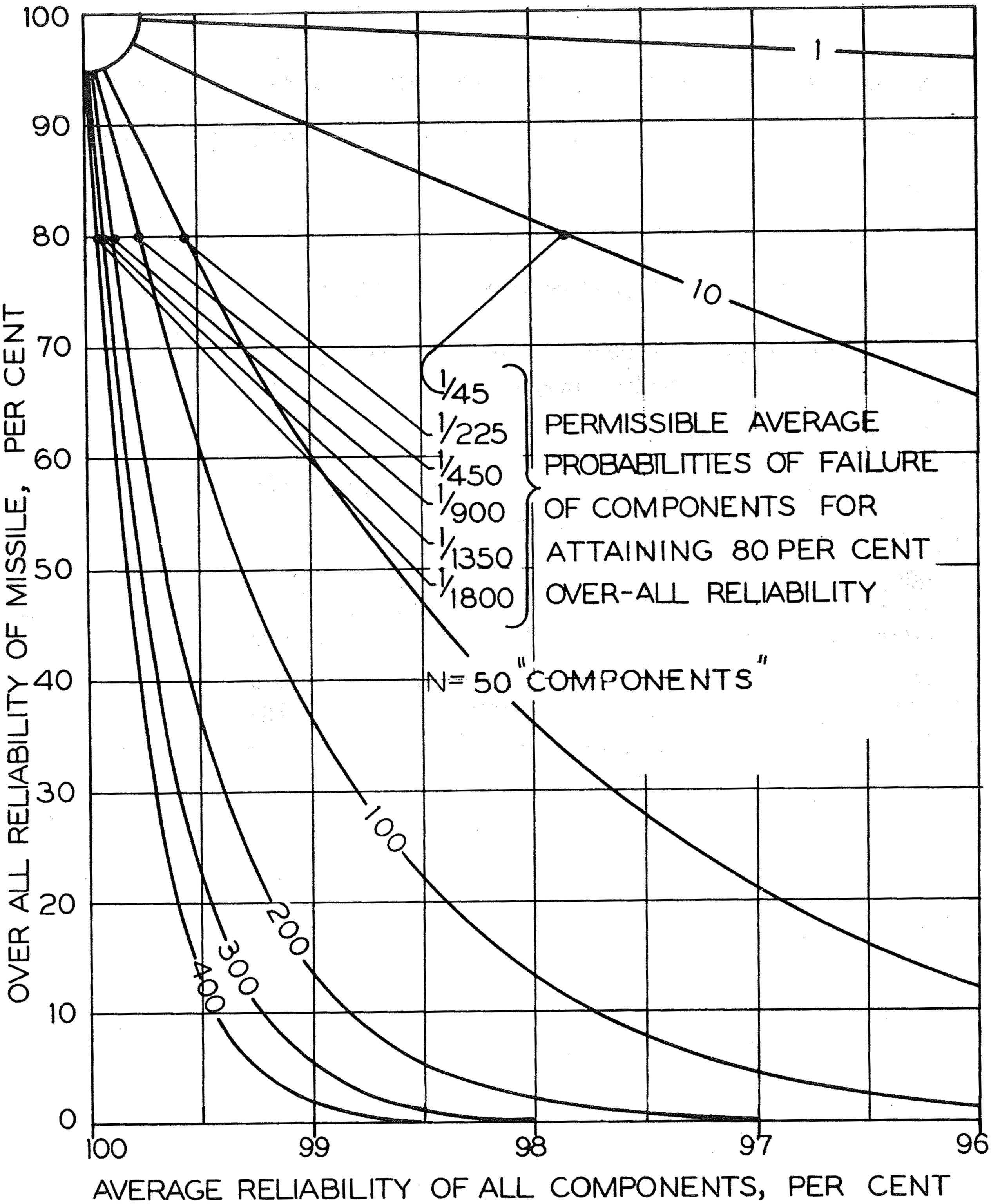
Application	Mission Time	Reliability (Probability of No Failure During Mission)	Mean Time to Failure (MTTF)
Aircraft	8 hours (without maintenance)	0.92	100 hours
Missile	1.75 hours (including tactical countdown)	0.99	175 hours
Satellite A (R&D)	1 month (720 hours)	0.96	25 months (18,000 hours)
Satellite B (Operational)	1 year (8,640 hours)	0.96	25 years (216,000 hours)

TABLE II

FREQUENCY OF PENETRATION OF ALUMINUM SKIN BY MICROMETEORITES

THICKNESS OF ALUMINUM SKIN *	FREQUENCY OF PENETRATION
.1 cm	ONCE EVERY 50 DAYS
.32 cm	ONCE EVERY 2000 DAYS
1.0 cm	ONCE EVERY 100 YEARS

* FOR SPHERE OF 3 METER DIAMETER



OVER-ALL RELIABILITY AS A FUNCTION OF COMPLEXITY AND RELIABILITY OF COMPONENTS

FIG. 1

to determine the magnitude of these strength variations, because the existence of a large variation could result in a high probability of failure.

Considering the fact that the failure rate of the critical parts of our aerospace systems may be only one permissible failure in 500,000 or 1,000,000, knowledge of the strength for these parts and its relation to the maximum environmental stresses to be encountered is absolutely necessary.

In order to determine the variation in the strength of a part or equipment it is necessary to "test-to-failure" samples of the parts or equipments. The results of these tests-to-failure can be plotted as shown in Fig. 2.

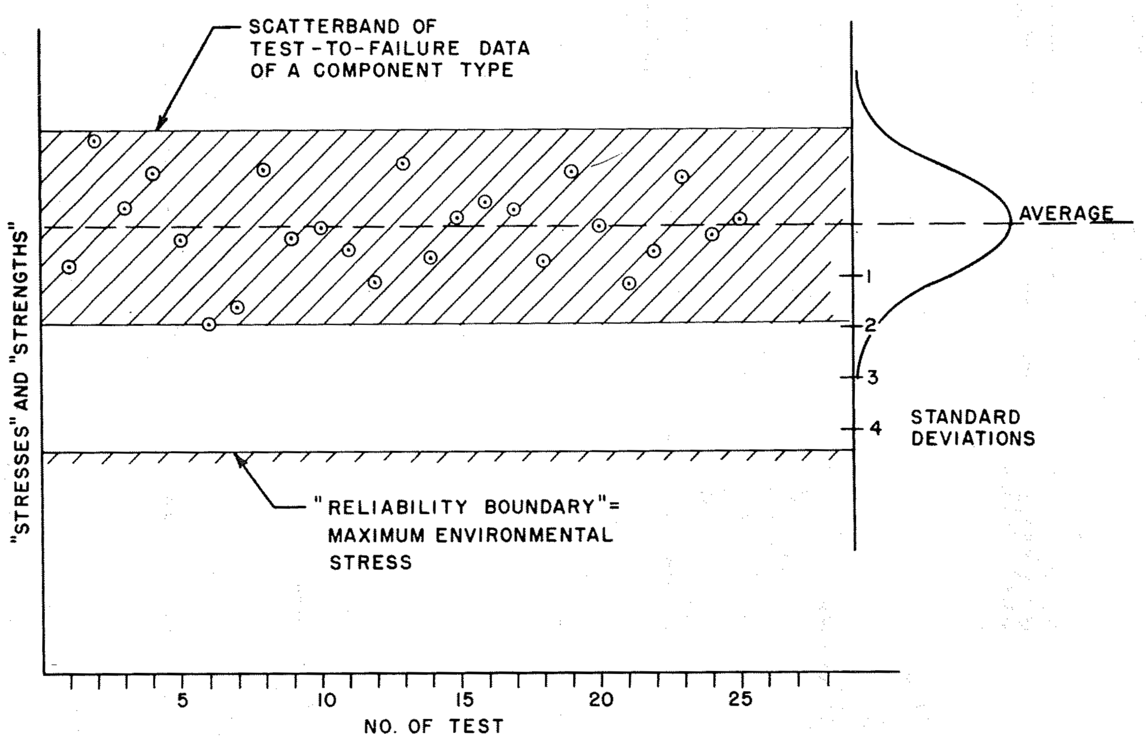


FIG. 2

VARIABILITY OF GAS VOLUME – U.M. 950ccFEI-M103EX SQUIBS

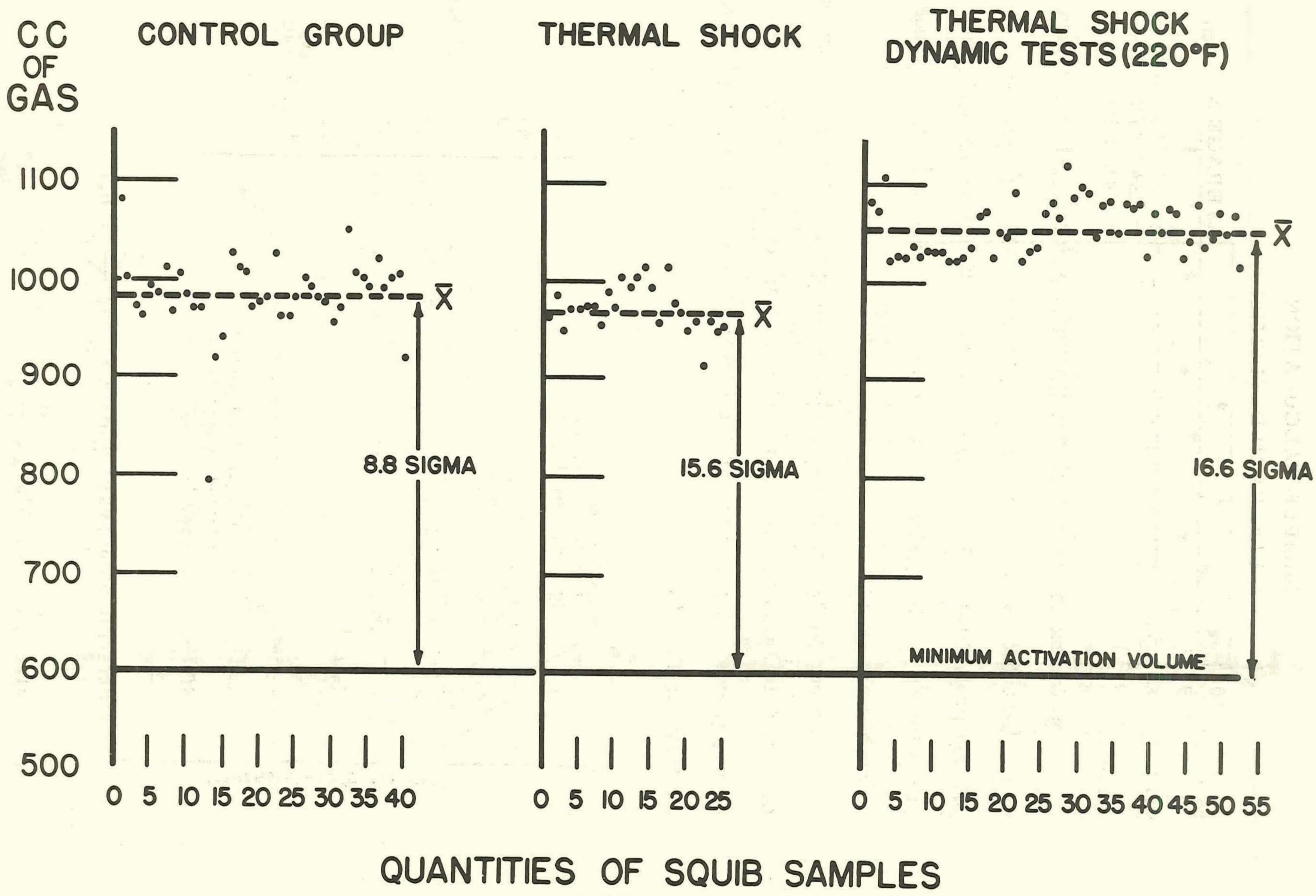
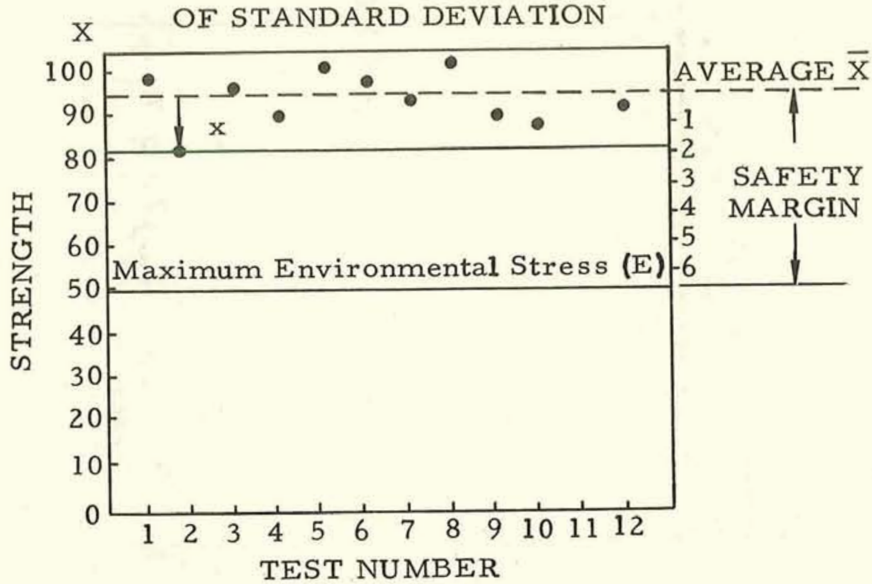


FIGURE 3.

APPENDIX

SAMPLE CALCULATION

OF STANDARD DEVIATION



TEST NO.	STRENGTH DATA	DEVIATION FROM AVERAGE	
	X	x	x^2
1	99	4	16
2	82	13	169
3	96	1	1
4	90	5	25
5	102	7	49
6	98	3	9
7	94	1	1
8	103	8	64
9	90	5	25
10	88	7	49
11	106	11	121
12	92	3	9
	$\Sigma X = 1140$		$\Sigma x^2 = 538$

Strength Average $\overline{X} = \frac{\Sigma X}{N} = 95$

Strength Standard Deviation $s = \sqrt{\frac{\Sigma x^2}{N}} = 6.7$

Strength Safety Margin $\frac{\overline{X} - E}{s} = \frac{95 - 50}{6.7} = 6.7$ Std. Dev.

TRANSIT RELIABILITY

Richard W. Cole
Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland

17293

Summary

The TRANSIT navigation system as presently conceived and planned consists of four satellites orbiting at 500 to 600 nautical miles in a polar orbit. Each satellite contains two high frequency transmitters whose frequency is obtained through multiplication from an ultra stable oscillator for doppler data plus a memory from which the satellites present ephemeris data is continuously transmitted in digital form using pairs of doublets with phase modulation on one of the high frequency transmitters. Any ship at sea outfitted with suitable receiving and computing equipment can determine a precision fix on its position by using only the doppler track and ephemeris data from a single satellite pass provided the pass falls within a suitable angle between the horizon and directly overhead. By using multiple satellites, frequent worldwide coverage is maintained and only a single injection station is required. The satellites will be launched into orbit using launching vehicles supplied by the Military. Economic factors make it necessary that the tactical satellites operate satisfactorily in the space environments for periods of time which are long when compared to present day ground equipment where maintenance is used to maintain continued operation. Maintenance in space is limited to a few vital functions via command link and redundancy is reduced to near zero by severe space and weight limitations. Satellite technology is a new endeavor for mankind which involves the many unknowns of the space environment. As a result, the Applied Physics Laboratory is making every effort to conduct a program which is balanced between research, development, and engineering whose program goal in reliability is to make a long operational lifetime in orbit an inherent "designed in" characteristic of the TRANSIT tactical satellites.

The TRANSIT navigation system as presently conceived and planned consists of four satellites orbiting at 500 to 600 nautical miles in a polar orbit. Each satellite contains two high frequency transmitters whose frequency is obtained through multiplication from an ultra stable oscillator for doppler data plus a memory from which the satellites present ephemeris data is continuously transmitted in digital form using pairs of doublets with phase modulation on one of the high frequency transmitters. Any ship at sea outfitted with suitable receiving and computing equipment can determine a precision fix on its position by using only the doppler track and ephemeris data from a single satellite pass provided the pass falls within a suitable angle between the horizon and directly overhead. By using multiple satellites, frequent worldwide coverage is maintained and only a single injection station is required. The satellite will be launched into orbit using launching vehicles supplied by the Military.

Reliability requirements ordinarily stem from performance requirements, economic factors, or both. In the case of the TRANSIT program, the Laboratory has been requested to extend the reliable lifetime of TRANSIT orbiting satellites to a goal of five years--a requirement often quoted today in Military contracts. A few of the factors which greatly complicate this task are as follows:

(1) New Environments
The characteristics of the outer space environments are not fully known, nor are the long term effects of these space environments upon electronics, electromechanical, and optical devices and materials known. With the present state of the art in vacuum technology, the extreme vacuum of outer space as projected by theory cannot be simulated on the ground. Our ability to simulate radiation, particularly nuclear radiation, is grossly limited and long term exposure as required in life testing is impractical. The large number of temperature cycles, with the associated thermal stresses, which a TRANSIT satellite would experience in five years may be a hazard to long life.

(2) Performance Demands Tax the State of the Art
In some areas, system requirements place severe demands on the state of the art with the resultant increased probability of degradation failures.

(3) Changing Technology
Electronic technology is in a constant state of evolution. This will result in changes in satellite design to improve performance, particularly in marginal areas, which changes introduce new techniques and hardware with the attendant reliability hazards.

(4) Miniaturization
Space and weight limitations force the use of ultra-miniaturization with all the attendant new techniques, parts, and materials. Fabrication becomes an acute problem because of the basic limitations of people to handle small parts and the limited production quantities make extensive tooling and automation prohibitively costly. People in some quarters feel that TRANSIT should use small launching vehicles for economic reasons, yet, since the limited payload weight capability of these vehicles requires the elimination of essentially all redundancy, the cost factors associated with the reduced reliability of these non-redundant satellites may result in a less economical "system" than one using the more expensive larger launching vehicles capable of a significantly greater payload.

(5) Long Operating Lifetime Without Maintenance
The required operating lifetime of the satellite without maintenance is exceptionally long when compared to present day ground equipment. With the exception of the transoceanic cables, all electronics today depend upon maintenance for continued operation, a procedure not presently feasible with satellites. The transoceanic cables, a simple system in comparison with a satellite, made liberal use of redundancy, a technique which can be used only sparingly in TRANSIT if severe weight limitations are imposed.

(6) Limited Space Trouble Shooting
Space and weight limitations severely limit the amount of telemetry which can be included for trouble shooting purposes while in orbit. Since the telemetering electronics itself will experience the satellite environment, it too presents a reliability problem. It is worthy of note, however, that in several cases, APL satellites now in orbit and operating successfully would have been total failures had not some telemetry and command functions been included which allowed some troubleshooting and correction.

(7) Statistics and Failure Loop Closure of Limited Usefulness
The fact that satellites will be produced in very limited quantities with but a few in orbit at any time, coupled with the evolutionary trend in technology means that techniques to achieve improved reliability through statistics and failure loop closure are of little usefulness.

(8) Extreme Cost
Each satellite which fails after being satisfactorily launched into orbit will represent a sizeable monetary loss.

From the foregoing, it follows that achieving a five year lifetime in orbit for TRANSIT satellites requires far more than a statistical prognostication by a reliability project or the preparation of voluminous high reliability specifications by a parts group.

Program to Date

When APL entered the satellite field in February, 1959, it recognized that the many unknowns of the space environment coupled with the effects which long term exposure to this environment might have upon satellite hardware could well make the road from the physics laboratory to space-worthy hardware an arduous one. Certainly, reliability in the connotation of five year life in orbit, could not be an initial requirement. However, research data vital to the development of the TRANSIT navigation system could be obtained from satellites having operational lifetimes in orbit in terms of a few months. It was therefore considered sound policy to launch experimental satellites as quickly as possible drawing upon the know-how of Laboratory personnel who had had extensive experience in guided missiles in an effort to obtain satellites quickly which would be as space-worthy as possible. In this way, the Laboratory would not only stand a chance of obtaining data vitally needed for the further development of the navigation system, but would also start to obtain first hand experience with hardware in the space environment. Dr. R. B. Kershner, director of the Terrier Missile Program for many years during which time he gained vast experience over the full span of technical management from system design to field operations, was appointed as director of the newly formed TRANSIT Division. The division was manned with assorted scientists supported by engineers and technicians, the majority of whom had had extensive experience in the Laboratory missile programs including the design, packaging, and fabrication of missile flight hardware and missile field test operations. From the outset, it was decided that the satellites should include both telemetry and command logic subsystems as a means of obtaining as much in-orbit information as possible and provide a means for limited corrective action. The satellite hardware designs have been the result of the efforts of teams consisting of circuit, thermal, and packaging design specialists and the flight hardware was fabricated by highly skilled technicians. The circuit design engineers, a lot of ultra conservative perfectionists, oftentimes themselves conducted the final bench testing on flight hardware and served on the field crews. Within the limits of time and manpower, the performance of each circuit was evaluated for variations in electrical parameters

of the parts, power supply voltages and impedance as well as temperature. Each satellite subassembly was subjected to several cycles of extreme high and low temperature to weed out faulty parts and solder joints, then the electrical performance was checked during vibration and over a range of temperature. Selective assembly was used in critical circuit areas and 100% screening inspection was imposed on parts believed to be critical circuit sources of unreliability. Redundancy was utilized in cabling and connector terminals as well as some important subsystems such as the stable oscillator and command receiver. The completed satellites were given an inspection critique by personnel not directly associated with the hardware, then subjected to a thorough system test both electrical and environmental including vibration and thermal-vacuum. From this point on, rigid rules of procedure were imposed to control all phases of the operation, which rules required extensive satellite retesting should any subsystems have to be changed.

The tempo of the program has been unbelievable. For instance, in the case of the TRAAC satellite, the time between the initiation of the design and the delivery of a fully tested satellite was 4 months. This included design, procurement, partial breadboarding, packaging, fabrication, checkout, assembly, flight acceptance testing, and delivery.

To date, eight APL satellites have been launched of which five were successfully placed into orbit. Of the eight satellites, four carried one piggyback satellite each and one carried two piggyback satellites supplied by outside agencies. Two of the APL satellites have portions of their payload powered by radio-isotope power supplies supplied by Martin under an AEC contract, the first nuclear power to go into orbit. The approximate electronic parts count for the earlier satellites was 1150 parts sans solar cells while the later satellites approximated 2000 parts. Experience with these satellites which may shed some light upon the reliability of satellites in orbit is as follows:

(1) After 24 months in orbit, signals are still received on two frequencies from TRANSIT IIA when it is in the sunlight even though a shift in the calibration of a thermostat resulted indirectly in the batteries blowing up.

(2) TRANSIT IVA is still transmitting on four frequencies after one year in orbit. The 2049 bit delay line memory has been loaded and read out repeatedly with but an occasional error. The RIPS is still operating satisfactorily but the commercially supplied telemetry transmitter failed early. Mode shifting of the command system has been experienced frequently, but this appears to be due to external causes (friendly jamming).

(3) TRANSIT IVB is still transmitting on four frequencies after seven months in orbit. All telemetry is operating and has held calibration amazingly well. The 1344 bit magnetic core memory has been loaded and read out repeatedly without error. The solar attitude detector indicates approximately 15 percent degradation of the satellites solar power generating capability due to radiation damage. Soon after launching, the satellite was successfully magnetically stabilized to within better than 2 degrees of the earth's magnetic field direction. On March 8, it was observed that the satellite was swinging greater than 10 degrees off stabilization. An analysis of the data indicated this was most probably due to the impingement of a micro-meteorite against the outer surface of the satellite. The oscillations of the satellite have subsequently damped out and the satellite is again aligned within better than 2 degrees of the local magnetic field direction.

(4) The TRAAC research satellite (standing for TRANSIT Research and Attitude Control) is still operating after seven months in orbit. Large quantities of radiation data have been collected using assorted sensors and a 256 bit digital telemetry system. Although the boom for gravity orientation did not deploy, the associated weighted spring bound by biphenyl did deploy demonstrating that the sublimation phenomena can be used as a control mechanism in space. Solar cell experiments have shown a 20% decrease in current output due to radiation damage. Due to the inclination of the orbits of IVB and TRAAC, these satellites spend considerable time in the inner Van Allen radiation belt. Thus, it is expected that the rate of radiation damage being experienced in these satellites will be considerably higher than will be experienced in the tactical satellites in polar orbits.

(5) People in some quarters have said that the tin in solder would sublimate in the vacuum of outer space resulting in a reliability hazard. As a result, two specimens of vacuum deposited 60-40 solder, each 0.8×10^{-6} inches thick, were located on the exterior surface of the TRAAC satellite. The resistance of these specimens was monitored to detect any sublimation or erosion of the solder. Results

after seven months in orbit indicate that there is no detectable change in the thickness or character of either solder sample.

(6) Extensive data reduction has shown that the long term stability of the stable oscillators in the vacuum of outer space is about a decade better than when at one atmosphere on the ground.

In spite of these encouraging results, the Laboratory is still of the opinion that the road to consistent five year life in orbit will be a difficult one.

As a result, the Laboratory treats reliability as a responsibility resting directly upon the shoulders of every division member be he the director, engineer, or technician. Reliability is considered in every decision along with performance, weight, power, size, cost or what have you. A separate reliability project serves a support function in the division. The modest budget of the TRANSIT program cannot support a massive reliability program. As a result, every effort is made to engage in those areas of endeavor which will produce the greatest yield. A very abridged description of these efforts is as follows:

1. The Laboratory will continue to orbit research satellites such as TRAAC which satellites will contain both experiments in basic research and reliability experiments. The basic research experiments will include typically (a) supplementary radiation measurements similar to those now in the TRAAC satellite to gather data in those areas where existing data is inadequate, (b) continued experimentation with attitude control, and (c) magnetometer measurements. The function of the reliability experiments is to develop directly a better understanding of the effects of the total space environment upon electronic parts and materials. For instance, a simple experiment was included in the TRAAC satellite where the frequency of an oscillator, using a unijunction transistor as the active element, was controlled by the RC time constant of a metal film resistor and a solid tantalum capacitor. In seven months that TRAAC has been in orbit, the frequency has not changed more than %. Our conclusion: Apparently the total space environment of TRAAC does not appreciably effect certain electrical parameters of these particular electronic components and, therefore, any efforts on these parts should be directed toward improving their catastrophic reliability. A similar "simple-minded" experiment is being designed to be incorporated into the next research satellite to check the β vs time of transistors fabricated in several ways. Attempts will be made to correlate these results with the results of transistors subjected to radiation on the ground. Simple experiments to evaluate materials in space are also planned. In this way we hope to determine where the big problems with the space environment rest.

2. The satellites will continue to be designed as conservatively as possible. Redundancy will be included where feasible and telemetry for limited troubleshooting in space. Analytical-experimental correlation studies will be conducted on each circuit to be followed eventually by optimization studies using advanced digital computer design techniques to achieve designs with the largest possible margin of safety against failure due to performance degradation.

3. The hardware will be packaged predominately with the welded matrix technique. Thorough thermal design studies, both analytical and thermal-vacuum will be conducted to reduce the maximum temperature of hot spots, keep average temperatures low, and keep temperature excursions small. Since the procurement of electronic parts with special weldable leads has been found to be impractical in many cases, a modest R&D program in welding has been implemented whose primary objective is to develop a better understanding of the factors which must be controlled to consistently produce reliable welds with ordinary lead materials.

4. Reliable parts are fundamental to reliability, therefore, the reliability project is expending considerable effort in this area. A programmable automatic semiconductor tester has been procured which is capable of collecting variables data. This machine will be used to 100% test all semiconductor devices used in satellite hardware, to collect parameter data required by the design engineers, and to collect data on the variations of the parameters during life testing. All data will be automatically recorded on IBM cards. Specifications are being prepared for every electronic part to be used in satellite hardware. These specifications will require a

100% screening inspection by the manufacturer as a means to weed out those parts potentially destined to early failure. 10,000 hour life testing during lot sample inspection will be a requirement on annual procurement with lot acceptance based upon the initial 2,000 hours. Study programs will be implemented to develop a better understanding of the application of critical parts such as batteries and solar cells and programs to develop more reliable parts supported as appropriate.

5. Pilot matrix test programs will be carried out on several parts to gain an insight into the required conditions for life testing. It has been the Military-Industry custom to divide qualification samples into groups and conduct life tests on one group. Life testing was ordinarily conducted at a constant temperature corresponding to the maximum rated temperature for the part. In TRANSIT, the parts will experience 30,000 temperature cycles with excursions from a few degrees for internal parts to upwards of 165°F for external parts. To achieve five year life in orbit, parts must be obtained whose failure rate approximates one failure per 500,000,000 unit hours in space after being exposed to preboost environments and launched into orbit. As a result, the conditions under which life testing is conducted may be a most vital factor to ultimately achieving reliability in satellite hardware.

6. A program to conduct matrix-life tests on electronic parts is being implemented to obtain the application data so vitally needed by the design engineer.

In conclusion, satellite technology is a new endeavor for mankind where the successful operation of complex equipment for extended periods of time in the total space environment is a requirement. As a result of the many unknowns associated with this new endeavor, the Applied Physics Laboratory is making every effort to conduct a program which is balanced between research, development, and engineering whose program goal in reliability is to make a long operational lifetime in orbit an inherent "designed in" characteristic of the TRANSIT tactical satellite.

OVERALL SUMMARY OF BELL TELEPHONE LABORATORIES PAPERS

If there is a single thread connecting this series of papers, it is economics as equated to survival. Reluctant as we seem to admit it, we are engaged in war with a remorseless enemy who knows what he wants. He has said that he will "bury" us. He isn't fooling. One of <u>his</u> major aims is the destruction of <u>our</u> economy. If we build weapons for effective fighting, but ignore economics to the point of national financial collapse, we shall have presented this enemy with the greatest bargain-basement victory in history. If we are to survive, every system we build must be an adequate system; it must be the one that will perform its intended function at the lowest possible <u>total</u> cost. First cost is not enough, because lowest first cost may involve highest total cost.

To build these excellent systems, we must pay whatever it costs to get components with the lowest attainable failure rates. There is no apparent limit to the variety of systems needed now, and to be needed in the future. However, all systems employ the same family of basic components. We need to do a thorough job of controlling their manufacture, inspection and use, in order that the highest reliability may be obtained. This must be done objectively, and we must not accept political interference. Moreover, we must keep a careful watch for improvements on old devices, and for the appearance of new devices, so that these may be subjected to the same controls.

Having the best possible components, we must choose the best design tools and reliability tools. We must develop a functional definition of failure for our system, and then must design each functional block so that it will cease working only when one of its parts fails. We must provide our equipment with the environment in which its components will actually give us all that we have put into them. We must seek simplicity of design, on the grounds that the simple think may work when needed; the more elegant arrangement may be impossible to maintain. In short, we must search our concept for frills and chop them out.

Having arrived at a preliminary design, we must assess its reliability with care; and we must reconsider the design of any portion whose ability to meet the total performance goals does not appear assured. Wherever possible, design must use old building blocks of high reputation, in order that the most may be realized from past investments -- and that our limited strength may be husbanded for use where really needed.

There will be times when it will pay to look at an old building block that has not performed well: It might promise highly-reliable performance if only minor changes were to be made; on the other hand, it might be a valuable text on what to avoid.

Design and reliability people must strive constantly toward the goal of economy, that is, lowest total cost of finished equipment. From the earliest development stages, we must be serious in our consideration of every trouble, and in our efforts to give the project the very best corrective feedback. When representative models are available, they must be tested exhaustively in the closest possible simulation of the final environment. And we must continue the process of trouble reporting and failure analysis even into the final use stage.

It has been shown that a new equipment derives its greatest benefits from failure analysis performed in the earlier stages, and that the chances of correcting troubles diminish as an equipment approaches tactical use. But we must try to know all we can, both good and bad, about each of our offerings if there is to be reasonable hope that the next one will be a lot better - that is, if it is to have a lower <u>total</u> cost.

THE ECONOMICS OF A RELIABLE SYSTEM

L. N. St. James
Bell Telephone Laboratories, Incorporated
Whippany, New Jersey

The Survival Concept

If a single theme can be extracted from everything in the known universe, it appears that this pattern can be labeled survival. In the animal kingdom this is particularly obvious. All normal individuals of every species breath oxygen, eat, propagate and each species is provided with a mechanism of defense against a hostile environment. The turtle has a hard shell, the bird has wings, the rabbit is fleet of foot. In the usual environment, not altered by man, the rabbit's speed does not insure a particularly high level of individual survival but the reliability of his propagating mechanism is generally adequate for survival of the species. It appears that the institutions invented, devised, or developed by man, the home, the family group, the church, the corporation, the state, and on up the ladder are also structured around the basic concept of survival.

Dexter S. Kimbal, a past dean of the Engineering College at Cornell told every freshman class, for years, that there is nothing made by man that someone cannot make a little bit worse and sell a little bit cheaper. This is survival at a low level, the individual or company level, or so it would seem. Supposedly the cheaper selling price would attract more sales in a competitive market and increase the company's profits. One cannot help but observe a relation between the worse and cheaper concept and survival under competitive bidding current in military procurement.

I learned of a small manufacturer recently who was making electronic gear, let us say test sets, on a military contract. He used no MIL specification parts. His reply, when questioned, was quite interesting and it would be true as of now. "These parts are just as good as MIL parts, they probably come off the same production line, and they save me about 20%". They could have come off the same production line, as MIL rejects perhaps, or they could have been made by a supplier, much like himself, who bought his raw materials on the basis of a trade name and 20% discount.

Of course none of us here is in this kind of a business; we all appreciate that the approach does not even promote individual survival on a long term basis. However, we do have to face a fact that has been often discussed. The military organization is required to pay from two to ten times (depending upon the source of the figures) the initial cost of an equipment for maintenance, just keeping it working, each and every year. Of course, when an equipment is being repaired, it is not performing its function, it is not working. Therefore, another equipment is required with its high maintenance cost to take its place. We actually pay in two ways, we have to buy two or more equipments to do a single job because the maintenance requirements are high. This seems silly but we are all aware that it takes 100 planes on a carrier to put 20 or 25 in the air. If each of us had to keep 4 or 5 cars in our garage in order to drive to work every morning, I am sure we would collectively find some other way of getting to work, even if it meant walk. Propagation of more equipments is not as easy for us as it is for the rabbit and this could be a major factor in the low survival rate of equipment species in the military field.

Sustaining The Defense Structure

We are all participating in one way or another in the building and support of a large military establishment. The taxes we and our companies pay buy the equipments and maintain them. Curiously enough, much, in some instances all, of our personal income and our companies' profits derive from the military purchases of new equipments, parts for maintenance and in a few instances maintenance and operation contracts. This looks something like a closed loop. Obviously it cannot be closed since out of these taxes must also come a whole host of costs for such things as government, management and labor which would make taxes far exceed income and profit if the loop were in fact closed. This loop must be supplied with energy from an external source which, in a restricted sense can be translated into dollars. This source can only be the general economy, the consumer goods industry. We are all interested in our individual survival, our companies' survival, and rightly so but if the dollars that can be drained from the general economy are not sufficient to build and maintain an adequate military establishment, the country itself cannot survive. It is necessary, therefore, that we direct a major effort toward this higher level of survival in order to make possible our individual survival. It is not someone else's job, it is our job. The cost of our defense structure must be reduced.

The Reliability Concept

If we look back into history a little, we find that some 30 years ago, the concept of quality control was introduced as a producer's tool to enable management to know what his shop was doing. This resulted in a better, more uniform product at a lower cost. Shortly thereafter, the basic tools of quality control were expanded into a much broader concept, a consumer function which, in the Bell System acquired the name Quality Assurance. This function can be delegated and, in the Bell System, in fact it is delegated to a separate organization in the Bell Telephone Laboratories which is even funded separately from the rest of the Laboratories. This organization is charged with the responsibility of providing assurance to the separate Telephone Companies that they are being supplied with equipments adequate for their needs at the lowest possible total cost. Total cost, of course, includes initial cost, maintenance cost, operating cost, etc. So far, there has been no need for a separate Reliability Organization on the Bell System side of the house.

In the military picture some years ago, equipments were getting more and more complicated. Much of it was down much of the time; it required huge stocks of spares and considerable time to maintain; but most important, at least so it appeared, it could not be counted upon when needed. Reliability looked like a panacea to cure all these ills 10 years ago. Now, we not only have Reliability, but we have maintainability, human engineering and value engineering and who knows what will be added next week, or next year. My guess is that the job will not be done until one of these specialities takes over the responsibility of demonstrating to the user that he is getting equipments adequate for his needs at the lowest possible cost. Are the people in Reliability big enough to assume this obligation? Some one must assume it if the country is to survive and few will question that individual survival is contingent upon survival of our country, our institutions and on down the ladder.

Reliability Definition

A few years back, the AGREE Committee produced a definition for Reliability with which everyone is familiar: "Reliability is the probability that a system will perform its intended function for a specified time under specified conditions of use". Where is cost in this definition? The definition is useful because, with certain assumptions that are now unreasonable, it can be specified, measured and demonstrated. Furthermore, if you bring in confidence you can give the statisticians a field day. So we all have fun but the user has to put in three systems where he needs one and he has to pour out several times the cost of each and every one annually to keep one working all the time. This gave birth to another definition, availability. This is defined as:

$$A = \frac{\Theta}{\Theta + \Theta_R}$$

where Θ = mean time between failures

Θ_R = mean time required to restore normal operation.

Still no dollars. Also a cursory inspection of this formula indicates that a very high availability can be obtained with a small mean time between failures provided that the repair time is short enough. Automatic identification and large plug-in units will accomplish this.

I should like to take this up later but, in the mean time I will propose a definition for an adequate system.

An Adequate System

An adequate system is the lowest total cost system that will do what the user expects it to do whenever called upon.

I would further propose that reliability engineers and reliability organizations orient their thinking and methods of approach so as to provide the user with assurance of adequate systems. A process for accomplishing this can be defined rather easily but its actual implementation by cook book methods remains to be developed. Figure 1 gives a diagrammatic version of the evolution of a system.

1. Derivation of Intended Function

It is necessary to assume that some specific problem exists and that a decision has been made to develop a system complex to solve this problem. The first obligation, then, is to derive the Intended Function for the system complex. It is probably easiest to convey the meaning of Intended Function by considering a simple example. Assume that the Intended Function is to detect certain types of targets appearing at some maximum rate, at some maximum density, at some specific velocity and with a specific lethal power. A complete statement of the Intended Function would embody a description of the target, assigning numbers to all such quantities as the maximum rate of appearance, density of attack, velocity and lethal power with the addition of the operating environment of the proposed system complex.

2. Derivation of Design Intent

In order to derive Design Intent for a single system it is necessary first to establish the general class of technical means. In the assumed example it will be radar. The rather general terms of the Intended Function such as, description of target, velocity and lethal power are translatable into Performance Characteristics, of the radar, such as range, sensitivity and rate of data acquisition while the assumed density of the attack is translatable into number of radars required.

This is completely orthodox but, if we are to think in terms of Adequacy from the user's standpoint we should go much further. Design intent can be considered best by dividing into two basic areas which are, in turn, subdivided.

A. Operational Capability

   (1) Performance Characteristics
   (2) Mission Reliability
   (3) Availability

B. Total Cost

   (1) First cost of a system
   (2) Installation cost of a system
   (3) Cost of operation of a system
   (4) Cost of maintenance of a system
   (5) Number of systems required to solve the total problem.

Obviously, A, the operational capability required of a system cannot be formulated until the Intended Function of the proposed system complex is well established. Equally obvious; the total cost, B, cannot be determined until the operational capability is at least tentatively established, and thirdly, it is evident that there are a number of possible solutions, only one of which optimizes all factors, at any stage of technical development including total cost. Only after this has been done is it possible to work out the detailed system design (Product Design) with any assurance that it will solve the user's problem at the lowest possible cost. The rest of Figure 1 will be discussed in later papers.

In recent years we have come to see Mission Reliability and Availability requirements in procurement specifications, usually in terms of their basic parameters, mean time between failures and mean time required to repair. This is wrong. Unless these requirements have been derived from the Operational Capability and total cost study just described under Derivation of Design Intent, they are likely to contribute little to relieving the current situation where it costs many times the initial cost each year to keep a system complex working.

Economic Factors

A number of years ago during the preliminary skirmishes with the ZEUS data processing system it became evident that we were rapidly approaching, if we had not already passed, some kind of a limit. The system would work, but it is doubtful if it would all work long enough at any one time to demonstrate that it actually was working. This forced a concerted drive in two directions:

1. Develop component parts with a lower inherent failure rate.

2. Design circuits that will make full use of the inherent failure rates of component parts.

Circuits could no longer be tolerated which would fail to perform their function before at least one component part had failed. This drive was not forced by economic considerations but two major economic conclusions derive from it.

1. The total cost of a system, considering first cost and annual maintenance cost, continues to decrease as the failure rate of component parts decreases.

2. We can afford to spend far more than is common practice to insure that each circuit in a system makes full use of the inherent failure rate of its component parts.

The first economic conclusion will be substantiated here but the second will be left for the next paper covering "System Reliability Estimation".

At least, as far as this has been explored to date, the total cost of a system to the user continues to decrease as component part failure rates are reduced. It seems unlikely that this decrease will continue indefinitely and an extrapolation of actual cost data indicates that an increase in total system cost can be expected around an average part failure rate of .0005% per 1000 component part hours due to an increase in component part cost.

Component Part Cost

Figure 2 shows the relative cost of a transistor as a function of failure rate in per cent per 1000 component part hours. At the far right we have the ordinary commercial grade, 29¢ each in lots of 1000, special discounts in larger lots. Around .05 or a little less we have the high reliability MIL specification transistors. This was the grade that we could not conceivably use in the ZEUS data processing system. Development work in the design of a suitable transistor, methods of manufacture and an extensive testing program were undertaken simultaneously. In the first stabilization of this process cost versus failure rate appeared to follow the broken curve (1). However, as the design and production processes matured and output increased, costs dropped and the curve merged into the line defined by the other points. With further increases in production, the cost might well fall below this line but the solid line is all that is known at present. Now if this experience is extrapolated to a .0001 failure rate the highest cost we could anticipate is represented by the broken curve (2), the most likely cost by an extension of the straight line. The failure rates on the solid straight line are actual failure rates observed in systems installed in the field.

It is not intended to suggest that we are the only ones sparking a lowering of component part failure rates. This is a rather general situation forced by large system complexes. Figure 3 shows relative cost versus failure rate

for capacitors and resistors. Although these component parts are used in the ZEUS Data Processing system, the component development work was done by others. The failure rates are again those observed in systems in the field. Curiously enough, these curves are also straight lines but if we knew more of the details they would probably show the same turn up on the left during the early phases that was previously shown for transistors.

System Cost

Figure 4 shows relative system cost as a function of the average component part failure rate. Down to about .001 failure rate in per cent/1000 component part hours these relative costs are derived from actual costs and in the extrapolation to .0001 they are based upon the expected cost increase shown for transistors.

Annual System Cost

Figure 5 shows annual cost curves for a system as a function of component part failure rate. The lowest curve shows annual maintenance cost. This requires some explanation. The replacement unit in the ZEUS Data Processing system is known as the D unit which contains, on the average 150 A packages. Failure of a D unit is indicated automatically and, in the basic system concept, a new unit can be substituted from stock in minutes. D units are repaired on site by locating and replacing the failed A packages. Annual maintenance cost per system, therefore, includes (1) the cost of the A packages needed for replacement, (2) the cost of maintaining a stock of D units, their repair and test, and (3) the cost of their replacement in a system; all multipled by the number of replacements required per year. The number of replacements is determined from the component part failure rate. Continuous operation is assumed in this estimate which is the expected situation. Actual cost of the replacement parts does not contribute very much to the total maintenance cost until very low failure rates are reached so the total maintenance cost is essentially proportional to failure rate except at the lower end of the curve.

The other three curves show the total annual cost which is obtained by combining the initial cost of the system with the annual maintenance cost. The upper curve is for a system with a life of one year. It is bought, operated and maintained for one year and then discarded. Actually, no one contemplates building systems with a one year life but showing this curve does enable us to see at a glance how little the first cost of a system contributes to the total annual cost when the usable failure rate of component parts is high. For instance, if it is known that a system costs about 10 times as much annually to keep it working as it costs to buy it initially, this curve can be scanned and it is seen that, where the relative annual maintenance cost is 380, the total cost is 420. The difference, 40, is the first cost of one system. It is evident, since 40 is approximately one tenth of 380 that a system that costs 10 times its initial cost to keep going for a year has an average effective component part failure rate of .04% per 1000 component hours. This is very close to the failure rate of high reliability MIL Transistors, but it is somewhat higher than for high reliability resistors or capacitors in well designed circuits.

Similarly, if the failure rate actually realized by the system can be reduced to .01, a relatively small reduction, the annual maintenance cost now equals the system first cost.

Now, if we really go all out to an average component part failure rate of .001 and design systems to make full use of this low rate, annual maintenance cost is only one twentieth of the first cost of the system.

The two middle curves are of greater interest because they represent the actual total cost situation. The 5 year curve applies to a single system with a 5 year life, so one fifth of the initial system cost is added to the annual maintenance cost to obtain the total annual cost. It can be seen that this total cost curve turns up at an average component part failure rate of .001. It can be concluded, therefore, that if such a short life is desired for some reason, the system need only be designed to make full use of parts with a failure rate of .001% per 100 component part hours.

In the lower curve, for a 20 year system, the minimum cost point is at .0003. The ratio between the annual cost of the minimum cost 5 year system and the minimum cost 20 year system is 50:18, nearly 3 to one. Of course, there is some doubt if component parts with a failure rate of .0003 are actually available but the 3 to 1 gain makes them well worth going after. Also, this does make us wonder if there is any rational reason for knowingly designing, building and buying a system with a 5 year life.

Annual System Complex Cost

Now I should like to return to the accepted formulation of availability.

Availability is defined as:

$$A = \frac{\theta}{\theta + \theta_R}$$

where: θ = mean time between failures

θ_R = mean time to restore normal operation.

It is evident that it is not the actual value of the repair time that is significant in determining availability but it is its relation to the mean time between failures.

Suppose, for example, that for the solution of some particular defensive problem, a single working system is required. The system selected

has an availability of 0.8. Now if we will be satisfied with defensive coverage 99% of the time, and using the binomial for calculation, we must purchase, install and maintain three systems where only one is actually required at any one time. This represents a tripling of total cost made necessary because the system has not been designed to really do the required job. The system is not adequate.

Now suppose that by considerable design effort the availability is raised to 0.9. With the same assumptions as previously made, two, instead of three systems are now required to assure coverage at least 99% of the time. This requires doubling, rather than tripling the total cost, a substantial improvement which would justify paying considerably more for a single system.

However, if we look at the problem from the high level survival point of view, can we really convince ourselves that any system with an availability of less than 99% is in fact adequate to do the required job? We should not have to purchase, install and maintain two or three systems where only one is required. And what is even more true, we can afford, on a total survival basis, to pay handsomely for this one really adequate system.

Availabilities of 99% are not by any means impossible. If we look at the structure of the formula, it is only necessary to so design the system that the time to restore normal operation is one one-hundredth of the mean time between failures. There are two avenues of approach which will, conceptually at least, achieve this 100 to 1 ratio.

1. Increase the mean time between failures.
2. Decrease the mean time required to restore normal operation.

If the second method is chosen, this will invariably lead, in a large system, to large plug-in assemblies and automatic trouble location of such defective assemblies. It will hardly ever be economical to discard these large assemblies so provision must be made for on site repair and adequate stocks to insure that the needed good replacements are always available. The actual maintenance load, therefore, has not been decreased but an additional cost has been incurred by the need for stocking and periodic testing of large replacement assemblies. This, therefore, is the less desirable method of securing a 99% availability and it should be used only after the first method has been fully exploited.

Figure 6 illustrates the magnitude of gain possible by fully exploiting the first method.

This chart is derived from the total system cost (Figure 5) previously used in order to show the effect on total cost to the user of a system complex. The relative cost on the ordinate has 3 scales the first for single system availability of 0.8 the second for 0.9 and the third for 0.99. It has previously been stated that the maintenance cost is not greatly changed by increasing the availability if this is done only by decreasing the time required to restore the system to normal operation. Therefore, since it takes two systems to do the job of one if the availability is reduced from 0.99 to 0.9 and three to do the job of 1 if availability goes to 0.8, our total cost to the user of the system complex is multiplied by 2 and 3 respectively.

Consider an example of an exceptionally well designed system which makes full use of component parts having an average failure rate of .01% per 1000 component part hours and intended for 20 year life. Assume, further that the annual total cost for such system is $100,000. However, because the availability of the system is only 0.8 it requires three systems in any complex to do the job of one. The total system complex cost, therefore, is $300,000 annually. Now if this system is redesigned to make full use of parts having an average failure rate of .001 the annual total cost per system will be reduced to $20,000. This, of course, brought the mean time between failures up to 10 times the initial value which, of itself, raised the availability from 0.8 to better than .95. Bringing in the second method of raising availability, a little further work along the lines of large plug-in assemblies and simplified, perhaps semi-automatic trouble location can lower the time required to restore normal operation and increase the availability to 0.99. Then only one system is needed to do the job formerly done by three systems.

Itemizing these numbers:

The total cost before redesign	- $300,000 per year
Total cost after redesign	- $ 20,000 per year
Saving	- $280,000 per year

It looks possible to drop our defense costs associated with system supply and maintenance to 7 or 8 per cent of what they now are if everyone is put on the team and plays the same game, survival.

It should be stressed again that we not only have to develop and make available component parts with inherent failure rates approaching .0001% per thousand component part hours but we also have to learn how to design systems that will actually realize, in operation, these lower failure rates.

Conclusions

Reviewing this discussion, we have endeavored to establish that:

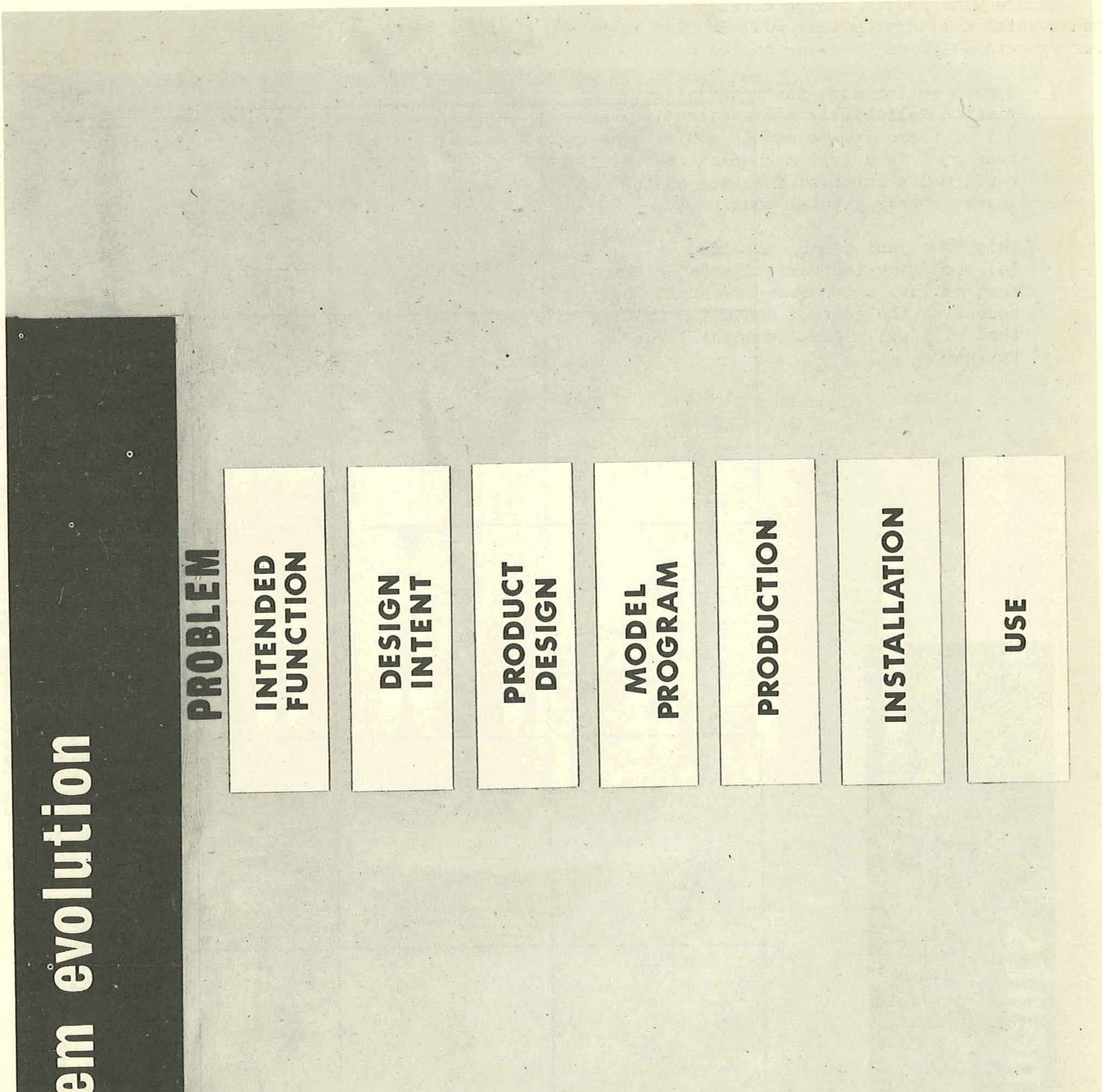
1. Our individual survival, our companies' survival and on up the ladder depends upon the survival of our country which in turn is contingent upon an effective military establishment.

2. An effective military establishment depends upon adequate systems.

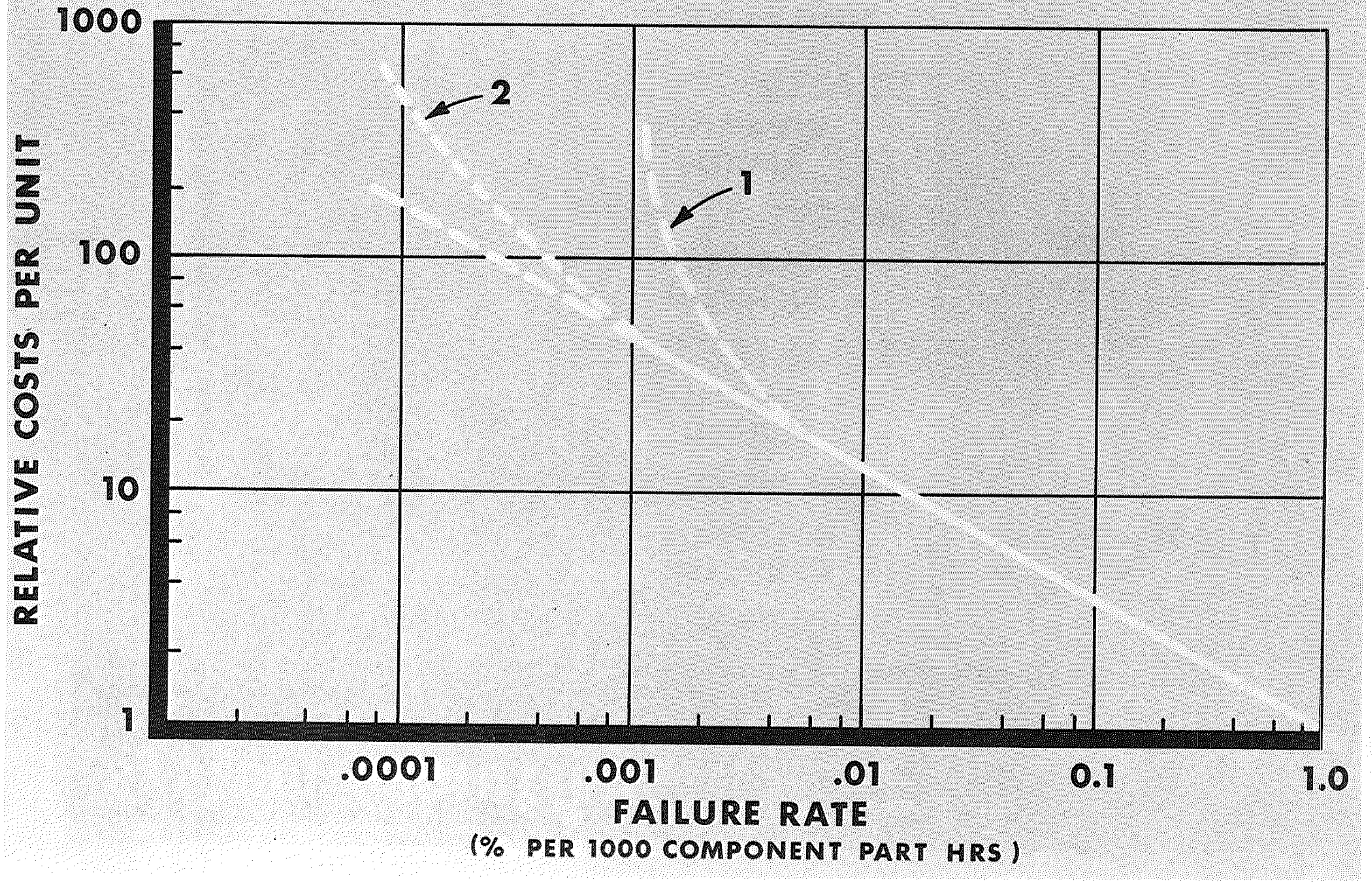
An adequate system can be defined as the lowest total cost system that will do what the user expects it to do whenever called upon.

3. System performance characteristics, Mission Reliability and availability are not of themselves adequate goals. The true goal is a system complex that will perform its intended function at the lowest possible total cost.

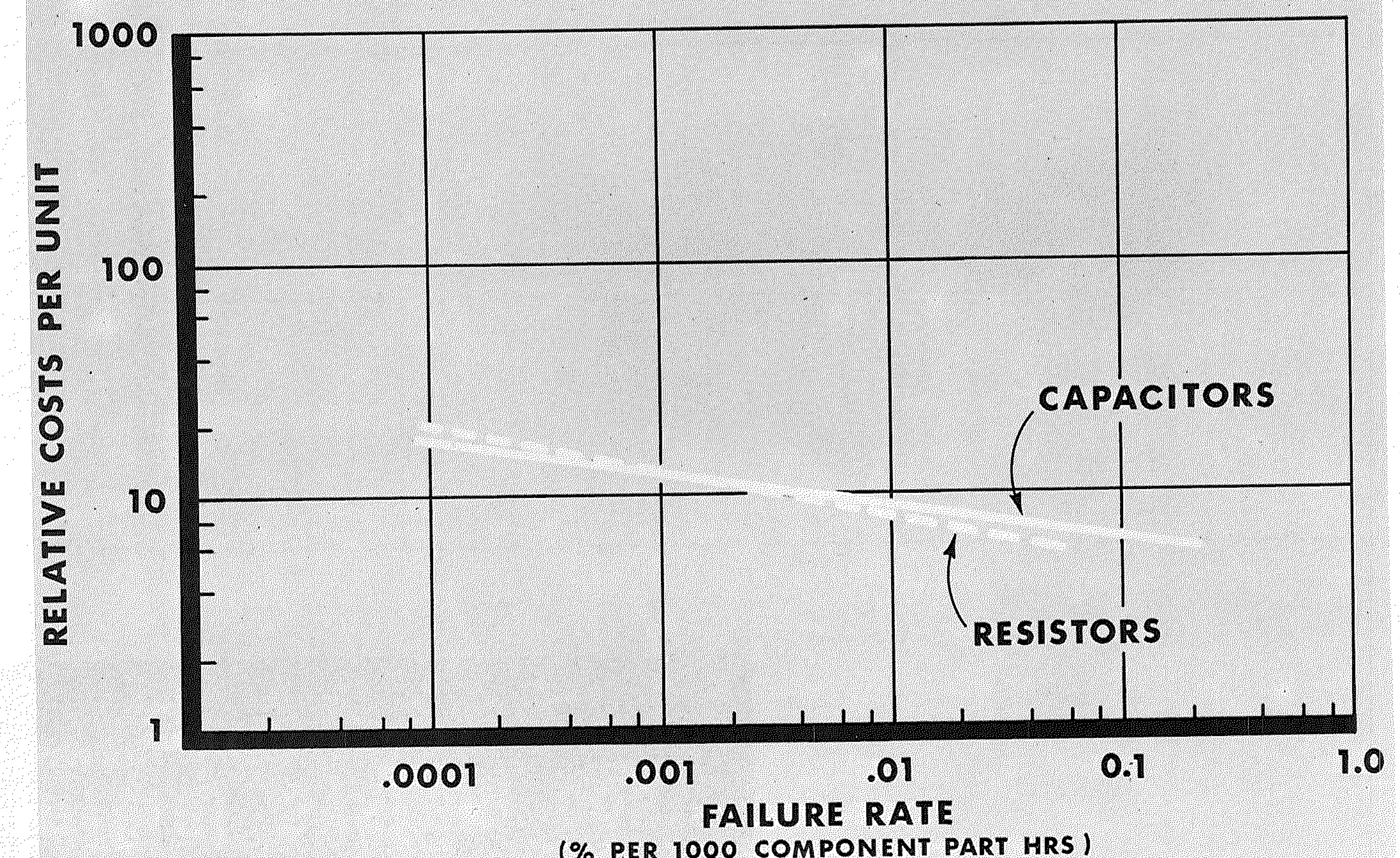
4. This true goal can be attained by, (a) accepting the cost of pushing component failure rates ever lower and (b) accepting the cost of designing systems that will fully realize these lower failure rates.


system evolution
PROBLEM
INTENDED FUNCTION
DESIGN INTENT
PRODUCT DESIGN
MODEL PROGRAM
PRODUCTION
INSTALLATION
USE

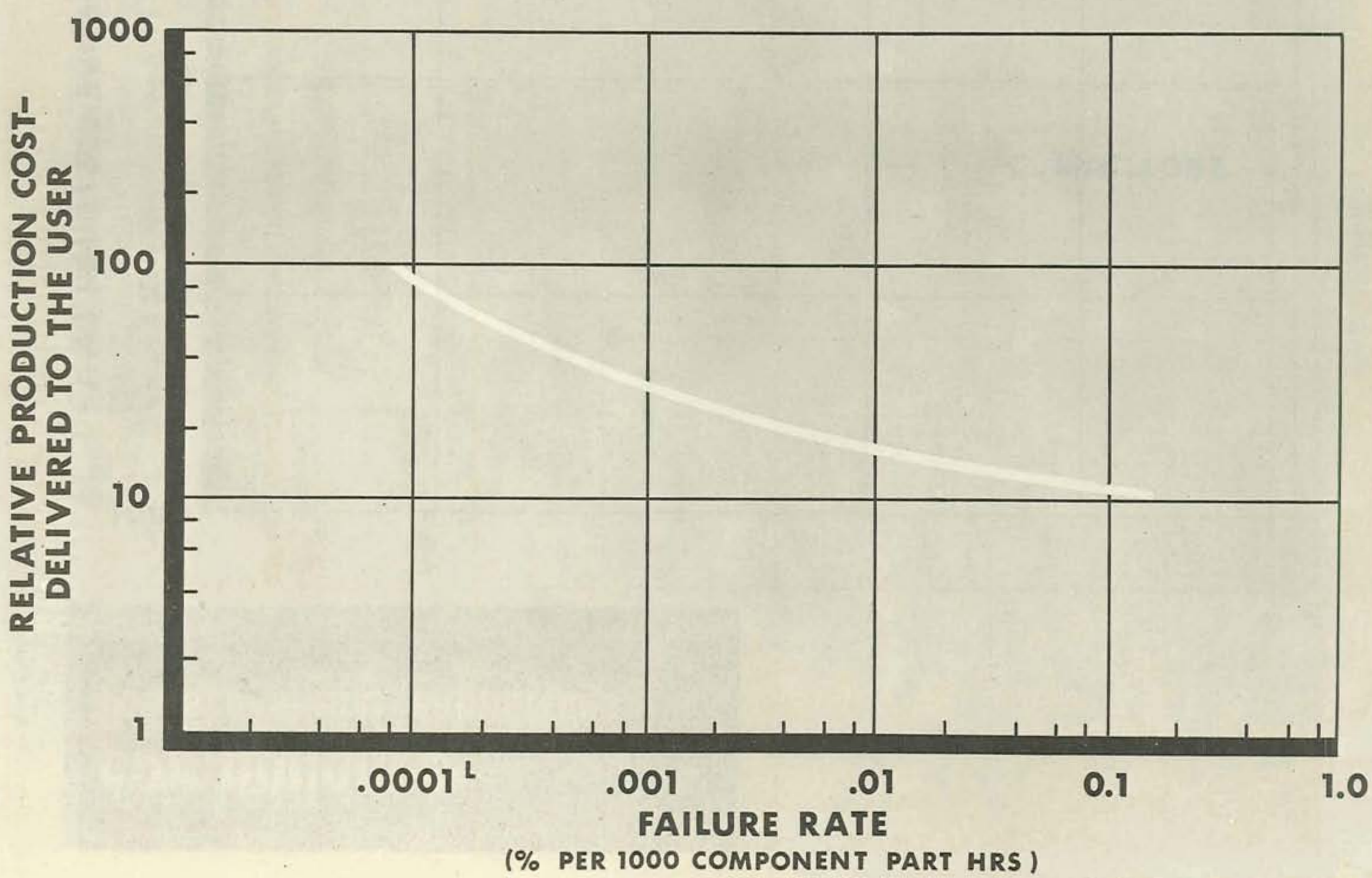
components
transistors



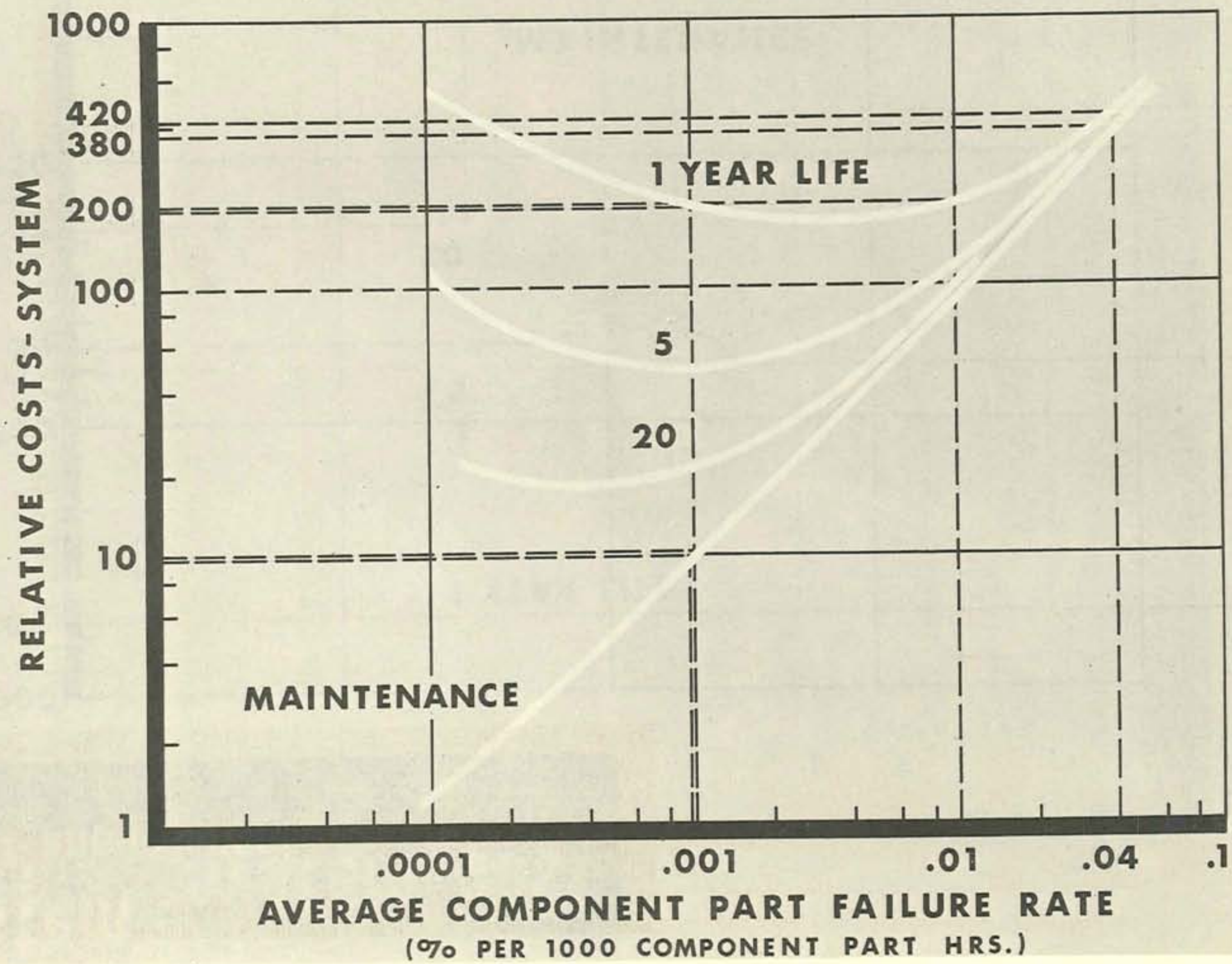
components
resistors and capacitors



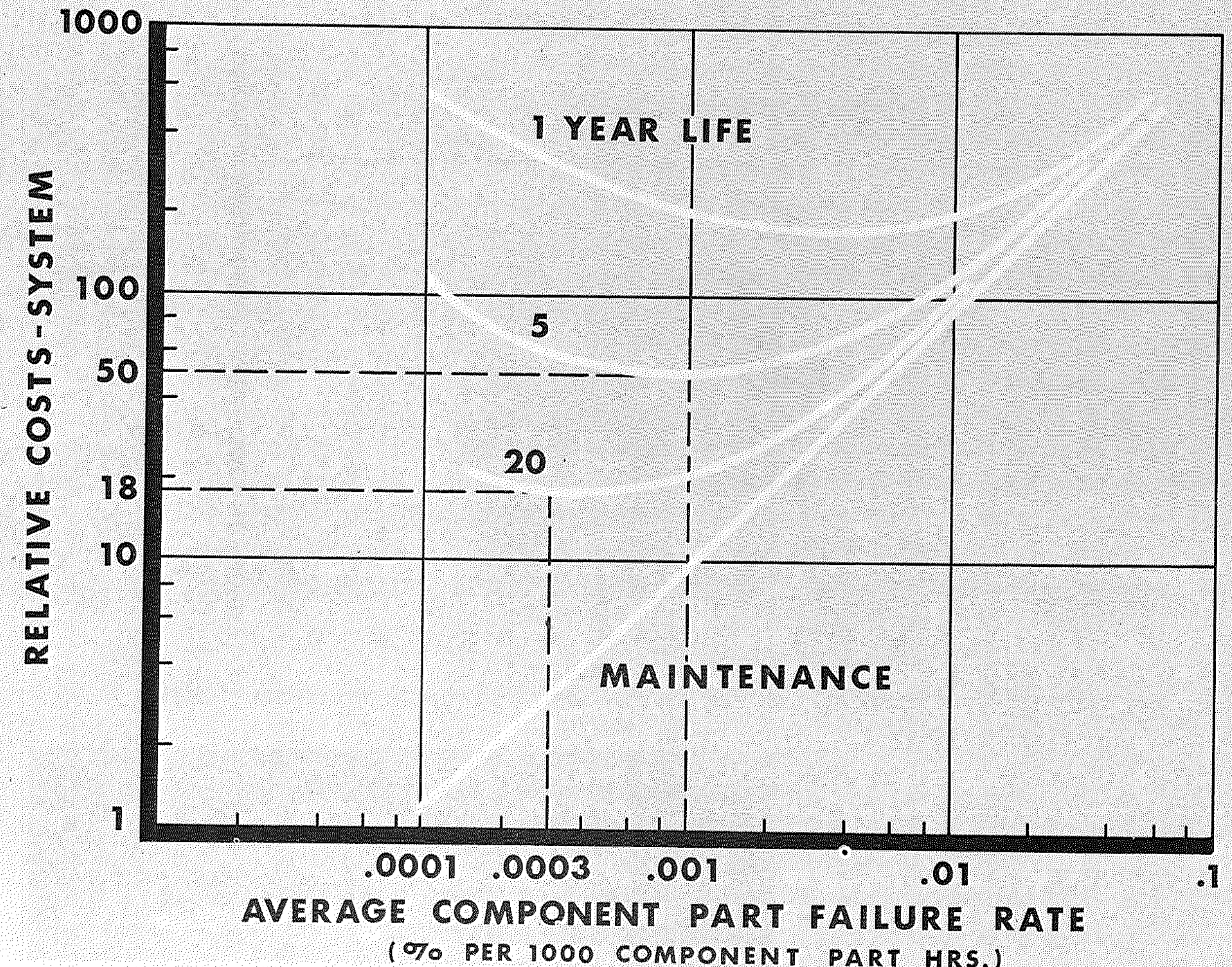
initial system cost

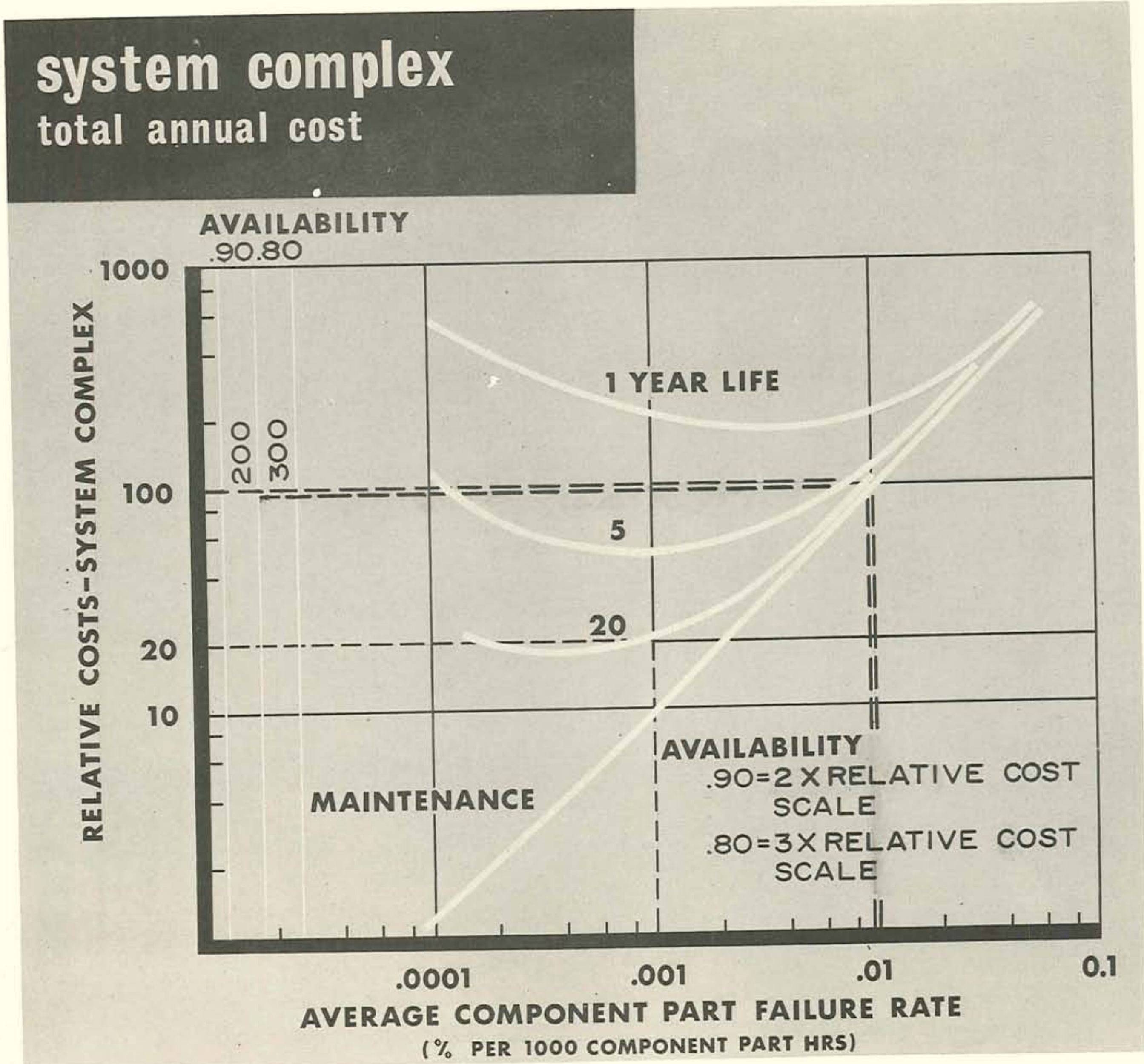


system
total annual cost



system
total annual cost




system complex
total annual cost
AVAILABILITY
.90 .80
1000
100
20
10
200
300
1 YEAR LIFE
5
20
MAINTENANCE
AVAILABILITY
.90=2 X RELATIVE COST SCALE
.80=3 X RELATIVE COST SCALE
RELATIVE COSTS-SYSTEM COMPLEX
.0001
.001
.01
0.1
AVERAGE COMPONENT PART FAILURE RATE
(% PER 1000 COMPONENT PART HRS)

SYSTEM RELIABILITY ESTIMATION

L. N. St. James
Bell Telephone Laboratories
Whippany, New Jersey

Introduction

It is essential that some device, process or method be available for estimating the reliability and availability of a system even when the system is only in the conceptual stage. This is not because reliability and availability are in themselves end points but because these factors must be known to a high degree of accuracy if an honest attempt is to be made to provide the user with a truly adequate system.

The previous paper defined an adequate system as the lowest total cost system which will do what the user expects it to do whenever called upon. Also, in the light of the economic considerations developed therein, we can put this definition into an operational form which fully covers the concept of "adequacy".

An Adequate System

An adequate system is one that makes use of component parts having the lowest possible inherent failure rate and is so designed as to actually realize this failure rate in normal use.

This is a fundamental and basic criterion for adequacy, necessary but not necessarily sufficient.

The second almost axiomatic rule, developed was:

A system should be designed so as to have an availability of at least 99%.

It is only by designing and manufacturing a system so that it is ready to perform its Intended Function substantially all the time, that we can avoid installing several systems when one system is needed at any one time.

Referring to Figure 1, the estimation process makes use of factors, such as effective circuit margins and general adequacy of design obtained from the use phase of earlier systems. These factors enter into the estimates developed for a proposed system first in the Design Intent phase and, later as design matures, into the Product Design phase.

In order to further define the reliability estimation problem and place it in proper perspective, it is desirable to repeat the definition of Design Intent. This was subdivided as follows:

A. Operational Capability

1. Performance Characteristics
2. Mission Reliability
3. Availability

B. Total Cost

1. First cost of a system
2. Installation cost of a system
3. Cost of operation of a system
4. Cost of maintenance of a system
5. Number of systems required to solve the total problem

Obviously, if we are to weigh various solutions to a given problem in terms of system performance characteristics, mission reliability and availability and evaluate these in terms of the various components of total cost to the user, we must have estimates of reliability and availability at least as good as the estimates of performance and costs. After the Intended Function of a system has been established and the actual design begins to develop, the estimating procedure must have within itself provisions for keeping it continuingly abreast of the system design. Only by such a process will it be possible to know in time to effect significant and necessary changes in the developing system concept whether or not reliability objectives are being jeopardized.

Reliability Estimation Process

The estimation of the mission reliability and availability of an electronic system are currently based upon a number of reasonable assumptions. Mission reliability is defined in the customary manner by:

$$P = \exp \frac{(-t)}{\phi}$$

where: P is the probability of success for a mission time t
ϕ is the meantime between failures of the system or the reciprocal of the failure rate.

Assumptions

Implicit in this, of course, is the first assumption. The times between failures are distributed exponentially or, stated another way, the failure rate of the system remains essentially

constant during its useful life. This, in itself, is perhaps among the least questionable of the assumptions required by the estimation process. In order for the probability of success so determined to have any real meaning to the user operating the system, lack of success, or failure must be defined in terms of the Intended Function of the system. This requires a second assumption. There is a sharp, identifiable line of demarkation between a system capable of performing its intended function and one that is not so capable.

In an extreme case, loss of prime power on a radar obviously causes radar failure. It is completely open and shut, there is no question. However, consider a radar whose Intended Function is to detect a target of some minimum effective cross section at some maximum distance and establish a track in some maximum time. There are obvious reasons for requirements of this sort such as the necessity to engage a target sufficiently far from its objective so that it will not do just as much damage as it would have if it actually reached its objective. Also, but perhaps less obvious, detection and establishing a track under limit conditions are not open and shut but are associated with a probability. This probability may be nearly unity or it may be 50% or less depending upon the system designer's embodiment of the Intended Function in his concept of Design Intent.

Now consider degradation of the loop gain of the transmitter-receiver of, say, 3 db, 6 db, 10 db, etc. This is definitely a reliability consideration but where does it fit in the basic definition of mission reliability? The truth is, it does not fit until some arbitrary definition of radar failure is set in terms of a supposedly rational interpretation of the Intended Function and its embodiment in Design Intent. This leaves considerable latitude for the worse and cheaper contingent to provide a radar with a very high calculated mission reliability that will hardly ever do what the user expects of it. It is little wonder that the term numbers racket has been applied to reliability estimation.

In contrast, consider the effect on a digital data processing system associated with this radar. It is composed of many thousands of logic elements and, in the usual reliability calculations, the failure rates of all logic elements are added to determine the total failure rate of the entire data processing system. Now in calculating a single track from data supplied by the radar and performing other manipulations required by the overall system, only a small fraction of these logic elements are used. The failure rate for the data system therefore, is pessimistic, much too high. This can compensate for a too optimistic definition of success in the radar case and it is this sort of thing that permits the numbers racket to get even close to the true situation if used with discretion.

In looking at the mission reliability estimation process from the bottom up instead of from the top down, a third assumption has obviously been made. Any large homogeneous population of like component parts has an inherent failure rate which can be considered to be essentially constant during the expected life of the system. This is certainly not tenable for wear out items, such as magnetrons and large klystrons. However, a system actually comprises heterogeneous mixtures of component parts and, with replacement of failed parts, the system approaches a constant failure rate.

The fourth assumption is that, in any system, these inherent failure rates are completely independent and therefore they can be added to get what we might think of as the lowest achievable failure rate of the system.

Failure Definition

It is probably best to consider the effect of the third and fourth assumptions on system reliability estimation jointly since they interact very strongly in the estimation process. We are first faced with the usual problem, what is a failure? In the component part field, a failure is seldom defined as a resistor becoming open or short but it is usually defined as a change in one or more of the important parameters of a component in excess of a specified amount. Definition of change as a failure carries over into the extensive life tests many of us have run over the years and it is exceeding some maximum change limit that we call a failure. The inherent failure rate, then, is in fact based upon a change greater than some arbitrary limit.

In line with the fourth assumption these failure rates are added to get the lowest achievable failure rate for a system. We look upon this simple addition as giving a goal that can be approached by a physical system but cannot actually be fully attained. If we concern ourselves only with meeting some mission reliability goal we need go no further than to decide upon some multiplier for this lowest achievable failure rate to give us the expected system failure rate. This expected failure rate multiplier can be determined from a review of the past performance of the design group involved together with a study of the current design. This has proved to be a satisfactory method in the past. If it is only necessary, then, to meet some stated mission reliability objective we can conceivably sign off even though the multiplier may be 5, 10 or even higher. Stopping at this point has certain attractive features, a relatively minor one being that it reduces the importance of the fourth assumption concerning the independence of component part failure rates which justifies their addition. The most attractive feature, of course, is that it permits the designer to carry over from earlier designs, concepts, solutions and even circuits and subsystems without anyone concerning himself with improving their failure rates. This saves development time and cost but is exceedingly expensive to the user and, from an overall standpoint, nonsurvival.

Total Cost Considerations

If we are to discharge our obligation to supply the user with a truly adequate system that he can fit into a truly adequate system complex, we must consider the total cost picture. In general, this leads directly to:

1. Use only component parts having the lowest failure rate now available.

2. Design the system to make full use of this low failure rate.

3. Design the system for an availability of at least 99%.

The first of these three statements has been shown in the first paper to be a necessity. Parts that are too good and too costly are not yet available. The second, however, involves some increase in design and development cost which may be substantial. However, if the total number of systems required is large, this increase becomes negligible from an over-all cost standpoint. Also, the third statement involves some increase in design cost in addition to an increase in the production cost of the system.

We would like to be in a position to evaluate these costs. However, we have not yet produced enough systems of enough different types to enable us to estimate the increase in development cost required to make the system failure rate no higher than the sum of the inherent failure rates of its component parts. Also we have not fully explored the requirements in design for a 99% availability. We can, however, make estimates of the maximum dollars that can be expended for these purposes on a relative basis and still break even. The number of dollars available is large.

Achieving Inherent Component Failure Rate

Figure 2 shows the maximum increase in design cost that can be justified in order to achieve in the system the inherent failure rate of component parts. Actually, in order to get this on a relative basis, a multiplier of the production cost of one system is plotted against a ratio, the effective failure rate of parts as used in the system divided by the inherent part failure rate. The curves for 10, 100 and 1000 systems represent upper bounds for the additional design cost that can be justified in order to realize the inherent part failure rate in the system. Any cost less than that shown on the curves represents a net gain in total cost to the user. Suppose we consider a specific value, a system that is so designed that the effective component part failure rate is 10 times the inherent failure rate, in other words, 10 times worse than it need be. As we all know, there are many systems in use that are not even this good. If the total requirements are for 10 systems, anything less than 80 times the first cost of the system can be spent to achieve in the system the full component capability. For a total requirement of 100 systems this limit becomes 800 and for the 1000 systems it becomes 8000. One system does not even show on the chart. However, this is only part of the picture, as will be discussed later.

This points out the futility of contracting for the design and construction of one system without full knowledge of total system requirements. There just is not the money available to design an adequate system on the basis of one. All possible corners must be cut and compromises made to make the design cost compare reasonably well with the production cost. Reliability, of course, is the first consideration to suffer and adequacy is never even thought of. When such a design is bought, we are stuck with it when future contracts are let to produce systems to fulfill actual requirements.

It is not only necessary to buy two or three times as many systems as are actually needed but each has roughly 10 times the maintenance cost of a truly adequate system.

If we continue this example of a system that started with 10 times the failure rate of the sum of its parts and assume that it had an initial availability of 0.8, just decreasing its failure rate increased its availability to better than 0.95. It is only a little way to the objective of 0.99. It seems reasonable to assume that this would not increase the initial cost to the user by more than 10%. Furthermore, the design cost should be very small, perhaps another 10% of the original system cost. In any event it is evident that there is a direct interaction between the effective failure rate of component parts as used in a system and the availability of the system so it is quite impossible to separate these effects.

Achieving An Adequate System Complex

Figure 3 shows the maximum number of dollars that can be spent to design a system that will make full use of component parts having a failure rate of .001% per thousand component part hours and with an availability of 99%. This value is plotted against the total number of systems required in a complex.

Since the determination of actual dollars available involves a comparison between what is currently being done and what conceivably can be done, it is necessary to start from an assumed base which is as follows:

System Design 1

1. Production cost of one system $100,000

2. Effective failure rate of parts in system .01%

3. Availability of system 0.8

An adequate system which appears possible within the current state of the art would have the following characteristics. It will be assumed that system design 1 can be converted to system design 2 with no significant increase in the production cost of one system. This is not quite true, but it greatly simplifies the calculations without materially altering the conclusions.

System Design 2

1. Production Cost of one system $100,000

2. Effective failure rate of parts in system .001%

3. Availability of system 0.99

A system complex requiring, for example, 10 systems operating essentially continuously would require the installation and maintenance of 30 systems of design 1 to do the job. However, for design 2, the availability is 99% and only 10 systems must be installed and maintained to do the job of 10. So far this cuts the total assumed cost to one third. Design 2 also drops the system failure rate to one tenth of the rate for design 1 and this cuts the annual maintenance cost to one tenth for each system.

The over-all result seems almost fantastic. If only 10 systems are required in a complex and each costs $100,000, we can afford to spend $28 million on the design to obtain an availability of 99% and achieve an effective failure rate of .001% per thousand component part hours. If the number in the complex is 100, we can spend $280 million and still break even. I doubt that anyone will contend that it is likely to cost more than a fraction of this amount to design a truly adequate system and anything less than these huge numbers is a measure of our chances of survival.

<u>Summary</u>

Money, alone, will not accomplish the job and, at the moment, no cook book rules have been written. However, certain general principles can be stated.

1. A truly functional definition of failure must be developed for a system.

2. Every circuit must be so designed that it will continue to operate as intended until at least one component part in it exceeds its end of life requirements. In other words, circuits must be designed in terms of the component part failure criterion actually used in evaluating component parts.

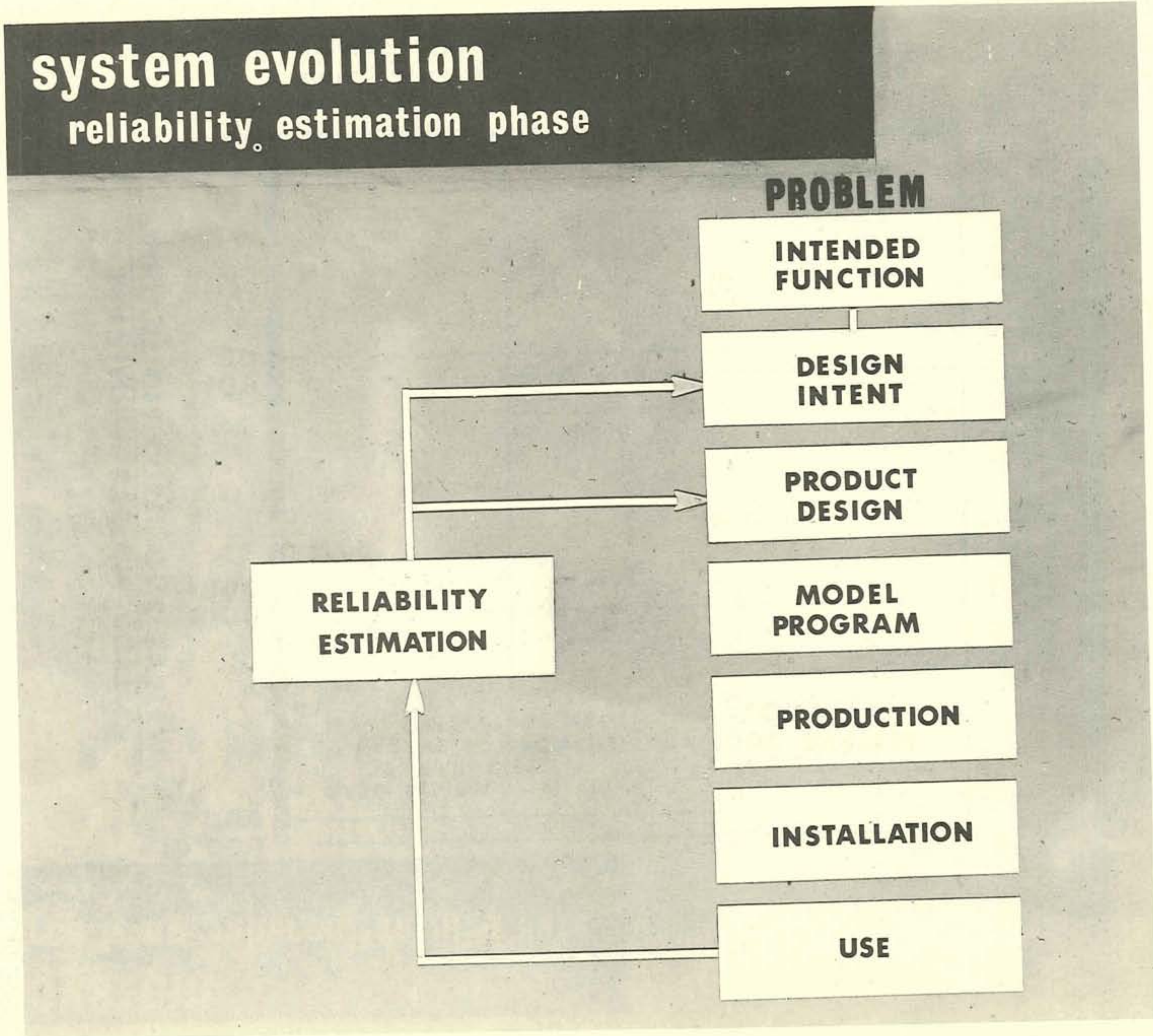
3. It is almost essential that ground based equipments and most mobile equipments be supplied with a temperature controlled environment in the order of 25°C.

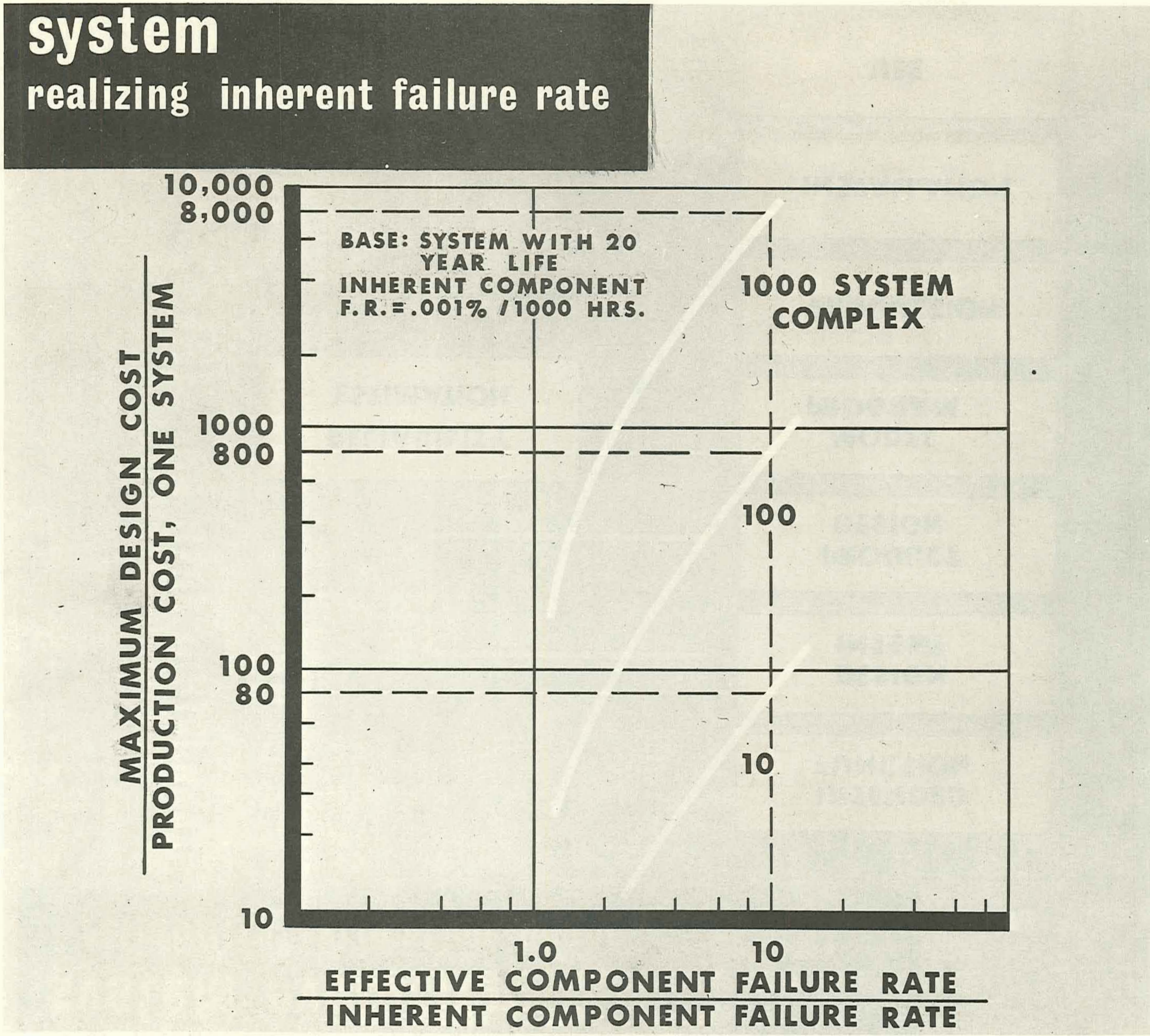
4. Circuits, plug in assemblies, subsystems, etc. should not be borrowed from earlier systems, with or without performance type modifications, unless it can be demonstrated from data that these units actually have realized the inherent failure rates of their component parts.

5. Explore for the simplest possible solution. Avoid hanging on gadgets to make a marginal design squeak through.

Many such things that we all do will readily come to mind. An awareness of the cost problem and its vital effect on survival should provide the will to change our ways and really design and manufacture adequate systems.

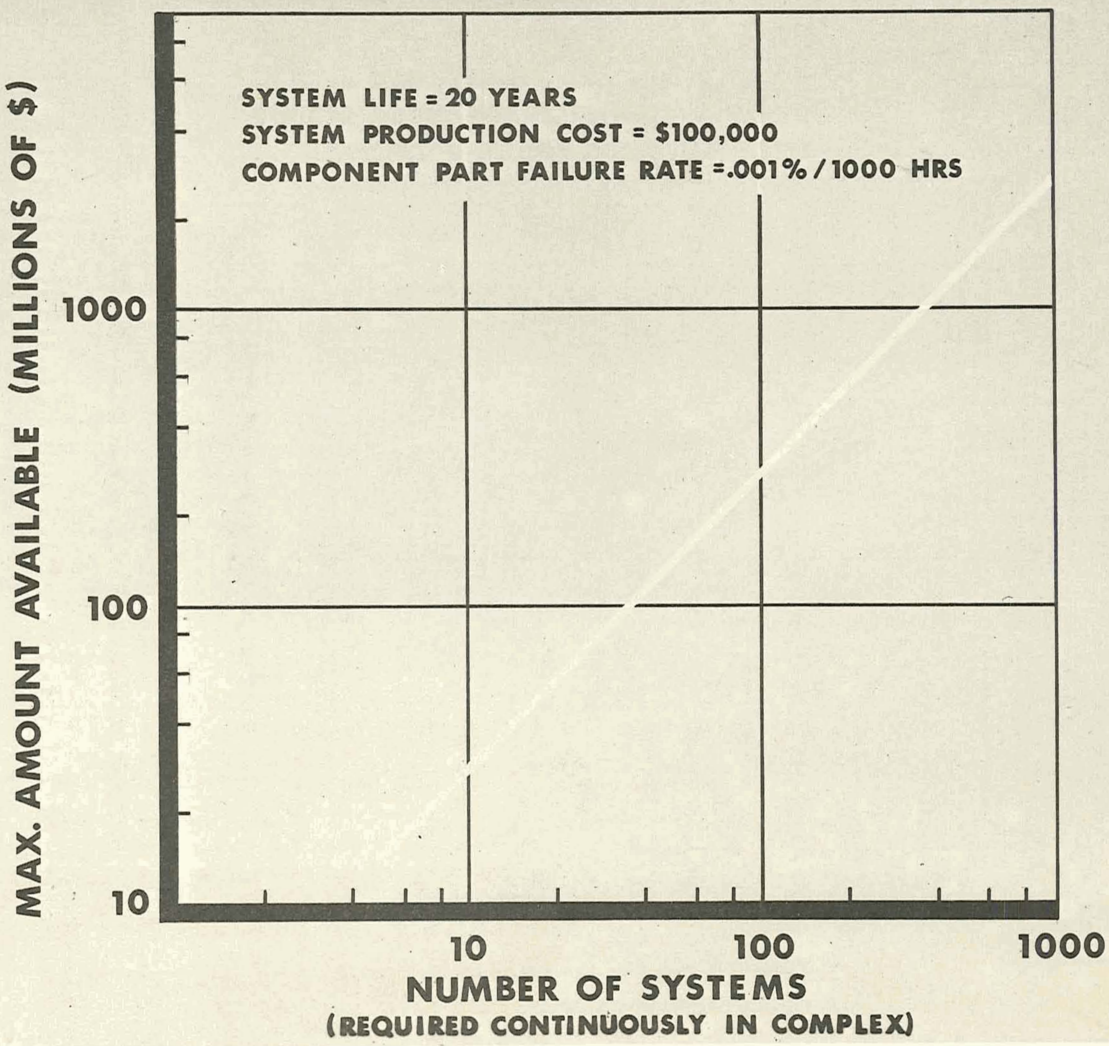
L. N. ST. JAMES


system evolution
reliability estimation phase
PROBLEM
INTENDED FUNCTION
DESIGN INTENT
PRODUCT DESIGN
MODEL PROGRAM
PRODUCTION
INSTALLATION
USE
RELIABILITY ESTIMATION


system
realizing inherent failure rate
10,000
8,000
1000
800
100
80
10
MAXIMUM DESIGN COST
PRODUCTION COST, ONE SYSTEM
BASE: SYSTEM WITH 20 YEAR LIFE
INHERENT COMPONENT F.R.=.001% /1000 HRS.
1000 SYSTEM COMPLEX
100
10
1.0
10
EFFECTIVE COMPONENT FAILURE RATE
INHERENT COMPONENT FAILURE RATE

system complex

securing adequate system design



SYSTEM RELIABILITY EVALUATION TESTING

G. A. Schiehser
Bell Telephone Laboratories, Inc.
Whippany, N. J.

A major purpose of system reliability testing is to provide information of value to the responsible organizations, whether they be administrators, designers, manufacturers or users. Any test or evaluation procedure which does not incorporate the necessary devices for providing the required information to these separate organizations, with widely differing interests and responsibilities, falls short of its primary purpose.

Referring to figure 1, showing system evolution, two principal reliability test phases have been added with their information feed back paths. On the left, the Design Verification test is shown with information deriving from the model program phase feeding back into the product design phase. Ordinarily, this may be considered as the primary channel However, all too frequently, Product Design (the specifications, drawings, test requirements, etc.) fails to fully reflect design intent. It is vital that the Design Verification Test shows up this failure so that necessary changes can be made in the specifications and requirements. It is generally agreed that this test should confirm whether or not the system conforms to the specified requirements, including the reliability requirements, and few will deny that the potential user should have access to these data if he so desires. The point that we are trying to make is that the information derived from this test must be much more than an estimate of the mean time between failures at some arbitrary confidence level.

Reflect upon the operational form of the definition of an adequate system as derived in the previous paper.

An adequate system is one that makes use of component parts having the lowest possible inherent failure rate, is so designed as to actually realize this failure rate in normal use and is designed to have an availability of at least 99%.

There are three distinct factors involved in this concept (1) use lowest failure rate parts, (2) design to make full use of this lowest inherent failure rate and (3) design for an availability of 99%. All three are basic properties inherent in the design, but the first need not be (and in many conceivable situations, cannot be) verified or demonstrated by a system test. The component parts used are specified on the drawings and it should have been previously ascertained that they have the lowest attainable failure rate. The system failure rate, or mean time between failure, has already been estimated and it has been confirmed that full use has been made of the inherent part failure rate. The 99% availability requirement can be expected to have resulted in a design with large plug in units which, when in trouble, are identified by some automatic or easily workable process. It would appear, then, that all we need to know is that the mean time between failures is at least as long as the estimated time and that the time required to restore normal operation is not more than one one hundredth of this. However, if we look at the total problem from the standpoint of the various organizations involved, we are again confronted with the situation of having done what is necessary but not necessarily sufficient. Let us refer back to the basic concept underlying the operational definition of an adequate system; that is, an adequate system is the lowest total cost system that will do what the user expects it to do whenever called upon.

From management's point of view, the design should be evaluated in terms of its Intended Function. Management might well settle for evaluation in terms of Design Intent if it can be shown (and this is usually possible), that Design Intent fully reflects the Intended Function. Furthermore, the manager is not interested in prolonged and expensive testing of many systems for show purposes, nor is he interested in delaying schedules and shipment dates beyond that necessary to establish one thing: Will the system do what is expected of it whenever called upon? He needs to know this not just to satisfy his contract obligations but, more importantly, to do what he can to insure his country's survival and thereby his company's and his own well being. Looking at management's basic question more closely, he has confidence in his designers and he has kept abreast of and taken an active part in the derivation of Design Intent and its expression in Product Design. If everything has operated without substantial error throughout this elaborate and complex process, an adequate system will and usually does result. The manager, therefore, is looking for undetected error.

Looked at from the system designer's viewpoint, he has done everything he knows how to insure that his creation meets the criteria for an adequate system. He has accepted the guidance of the reliability group and they have been mostly right in the past. Summed up, he feels confident, entering into the Design Verification test, that his design will do what is expected of it whenever called upon. However, he knows that engineers are human and they do make errors, infrequently perhaps,

but none the less errors. What he asks of the Design Verification test, then, is a high level of assurance that, if errors have been made which will significantly jeopardize the adequacy of the system, such errors will be exposed to view as rapidly as possible. He also reiterates management's viewpoint concerning schedules, not because he automatically thinks along these lines, but because his survival depends upon his support of management.

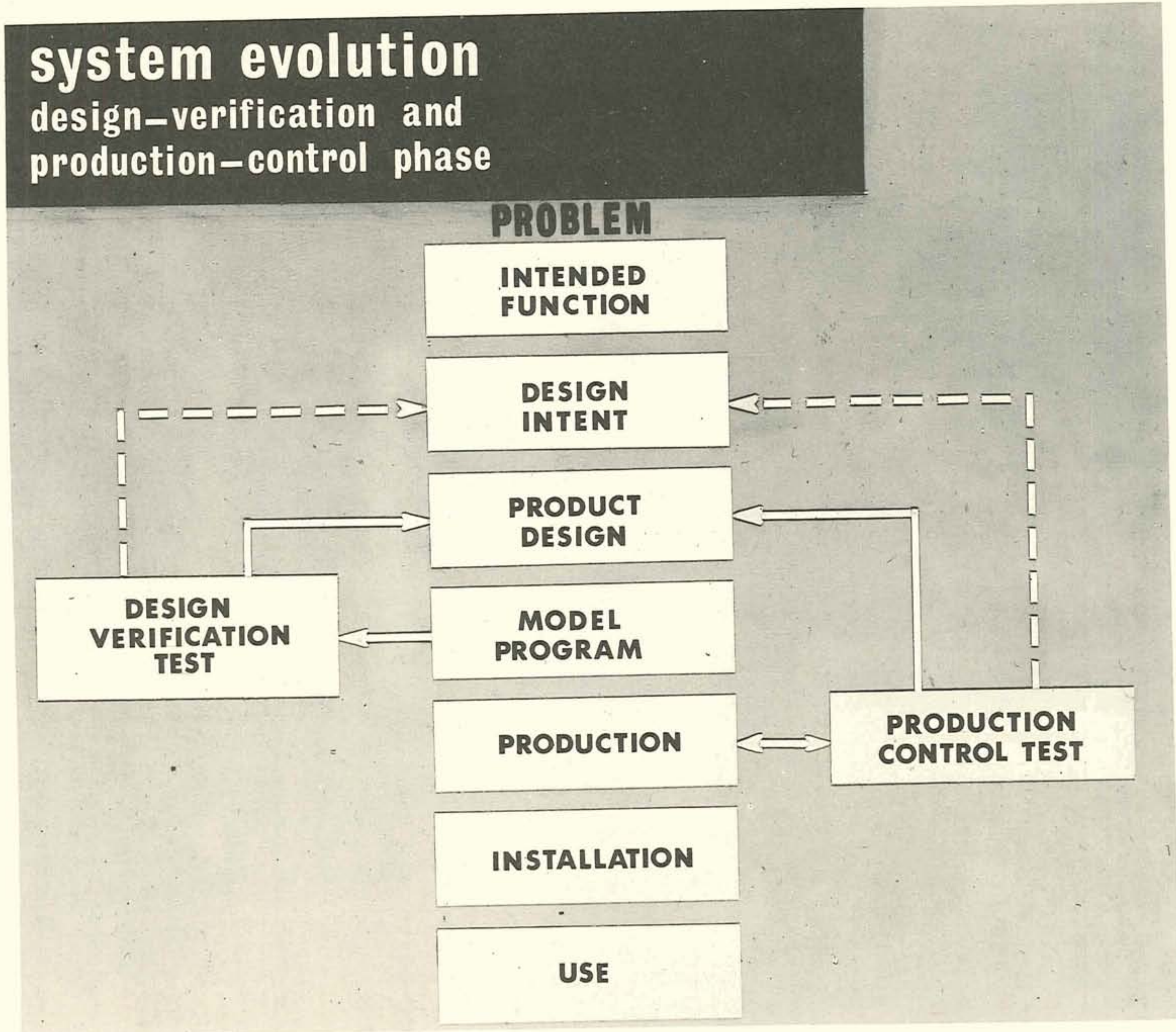
Now if we expand this thinking to cover production control tests and refer again to figure 1, the information is shown to derive from the production phase and to feed back into production. It also feeds into the two higher levels, Product Design and Design Intent.

In this case management's questions are the same except now they are asked of the overall production output. The designer's questions are also directed toward the total output of production but they run more along the lines of, "Has anything happened in production to deteriorate significantly my previously established design?" Of course, his original questions are still asked concerning errors, since there is always a possibility that design errors which existed originally were not detected in the earlier Design Verification test.

Added to this group we have the production engineer. He desires assurance from production control tests that he will know promptly if his manufacturing, inspection and test processes have permitted product to deteriorate significantly below the capability inherent in the design. With assurance that this has not occurred, he can feel confident that his product will do what is expected of it whenever called upon.

Reflecting back over this discussion, all the functionally involved groups are looking for the occasional error. If none has been made, the Intended Function will be met by production systems and this includes the mean time between failures and the mean time to restore normal operation. Reliability testing should be directed toward the much broader objective of answering the specific questions of the functionally involved organizations, which reduce essentially to error detection rather than to the 90% confidence demonstration of mean times which is becoming currently popular. It is only by such a complete process, as is described in this series of papers confirmed by an error detection test, that the user can secure assurance of adequate systems.

Unfortunately, we do not have all the answers to this problem of error detection. To date, we have tried several procedures which have been more or less successful but none have proved ideal. The objective should be to devise test procedures that will yield a high level of assurance of detecting any significant errors in this elaborate and complex process which we have labeled System Evolution.


system evolution
design–verification and
production–control phase
PROBLEM
INTENDED FUNCTION
DESIGN INTENT
PRODUCT DESIGN
MODEL PROGRAM
PRODUCTION
INSTALLATION
USE
DESIGN VERIFICATION TEST
PRODUCTION CONTROL TEST

CONFRONTING THE ENVIRONMENT

T. B. Delchamps
Bell Telephone Laboratories, Inc.
Whippany, N. J.

17294

SUMMARY

This paper highlights two areas in the environmental field requiring a more imaginative and objective meeting of design and reliability functions. Thorough and timely environmental definition, as an essential ingredient of successful system design and meaningful reliability estimation, is discussed. Two examples of current importance in the areas of missile-vibration and space-environment simulation are briefly reviewed.

INTRODUCTION

In biology, adaptation is defined as the "modification of an animal or plant (or of its parts or organs) fitting it more perfectly for existence under the conditions of its environment." Being of patient disposition, nature waits for trouble to appear, and casually proceeds to handle it. In systems development, however, we cannot afford the leisurely approach. Here, the degree of success is measured by our ability to make most of the "modifications" during initial design. For this, we must have a fairly good idea of what the environment will be. Further, what we don't know in advance about the environment must be learned at the earliest possible moment. One suspects that nature has been rather more successful in coping with environmental problems than her human offspring. Clearly, improvement in this situation is everybody's problem.

The role of Environmental Engineering in systems evolution is shown in broad outline on Figure 1. The degree to which the Environmental Engineering effort influences product reliability depends directly upon the quality, quantity and timeliness of the prediction, definition and simulation functions indicated. This theme will be further developed in the following.

ANATOMY OF FAILURE

In the early stages of system evolution, it is expected that those with concept responsibility will remain somewhat aloof from physical reality. Barring measures to the contrary, however, the initially-justified oversight is repeated and compounded by others in frenzied passage through various stages of detail design, model fabrication, and laboratory qualification, culminating in grand climax with field evaluation tests. Timing considerations having displaced reason and judgment, the system quite frequently fails on schedule. What follows is costly, time-consuming and often involves compromise of mission performance. As with the man matching pennies, the accrued deficit is virtually beyond recovery.

This is not to condemn the schedule per se, as it is normally an effective instrument of orderly progress; nor is it intended to lay blame on the conceiver, who after all is encouraged to function in the near abstract. Rather, it is to suggest that the tyranny of time frequently degrades quality of effort by stifling the exercise of vision and review as vital and continuing forces in development. Further, we sense here a basic weakness in our developmental philosophy, which permits discrete specialties the luxury of mutual indifference, and fails in maximum utilization of total information available at any given moment.

TOO LITTLE, TOO LATE

There is perhaps no better example of this organic ailment than industry's collective failure to deal effectively with the environment. Here is a formidable adversary demanding early recognition, definition and vigorous sustained action in defense of program goals. Elaborate facilities and myriad specifications notwithstanding, the full potential of environmental cognizance is simply not being realized. Indeed, design, prediction and laboratory evaluation based on careless, unsupported and unconfirmed assumption, frequently serve to degrade the product and cloud the reliability picture. Through a combination of late and limited attention to environmental definition, and inadequate simulation techniques, the true determination of product reliability remains in default until the field-evaluation phase, when the opportunity for corrective action has all but vanished.

Forces resisting improvement in this situation include rigid schedules, budget constraints, provincial attitudes, indifference and even antagonism toward any departure from the traditional terminal evaluation. There is no pat solution to this dilemma. The first step may be recognition of the problem as an essentially human one, with the mere physical aspects quite susceptible to imaginative treatment. In this vein, it would seem appropriate to focus strong attention upon thorough environmental definition as a key ingredient in system development, demanding careful estimates, earliest possible confirmation and continuing review from initial concept through tactical capability of a given system. The companion

problem of how best to simulate environments of importance, tends toward ready solution once the essential facts are known.

THE PRICE OF IGNORANCE

Ascribing broad connotation to the terms stress and strength, we can apply these terms in a general way to any physical situation we wish. Specifically, we can state that failure occurs when stress exceeds strength. Postulating a normal density function for stress level, and assuming that strength is also normally distributed (but advancing no theories in either regard), we will now examine the probability that stress exceeds strength under various combinations of mean and variance for each distribution. The severe penalty associated with careless assumption of these properties for design purposes, or failure to recognize their variability, is implicit in this discussion.

Referring to Figure 2, the expected penalty in failure frequency imposed by high variability and low mean offset in stress and strength properties, is quite obvious. Conversely, the benefits accruing from low variability and high mean offset are equally apparent. While there is nothing particularly surprising about these properties, the relationships presented serve to emphasize the vital role of early and accurate environmental definition in successful system development.

Having established a general viewpoint, we will now examine some specific effects of error in assumed environmental stresses. As we proceed, it should be remembered that the errors in question, though like in effect, may arise either through justified lack of prior knowledge of the environment, unjustified failure to extract such knowledge from early experiments, failure to allow for variability in measured stresses, or just plain carelessness in measurement or assumption. The first error mentioned above must be accepted and allowed for; the remaining three must not be tolerated.

Referring to Figure 3, we observe the established failure response of mica capacitors to increased temperature. Note that an arbitrary base level of 30°C has been assumed. Apart from the familiar acceleration characteristic shown, and its effect on replacement requirements, the significant property inviting recognition is the increase in sensitivity to variation at higher temperatures. For example, moving from 50°C to 60°C along the acceleration curve nearly doubles the effect of a 10°C variation in temperature about the levels assumed. This is the kind of physical reality so often ignored in the casual selection of environments for reliability estimation and evaluation purposes. Under these circumstances, prediction and sample parameters, upon which critical program decisions frequently depend, are rendered meaningless.

Another example is presented on Figure 4 for germanium semiconductors. The foregoing comments apply equally well in this case, with one exception. The effects in question become less pronounced as dissipation level is reduced.

An important environmental property of Nickel-Cadmium cells, currently popular in satellite applications, is presented on Figure 5. This example involves the simple supply-and-demand relationship of a solar power plant. When converted solar energy exceeds dissipation within the satellite for extended periods, an overcharge condition develops. Tolerance to this state is essentially a function of cell temperature, which determines the voltage level at any given charge current. Cell voltages above about 1.5 reflect a fully-charged negative electrode, and signal the evolution of hydrogen at a faster rate than it can recombine at either electrode. The associated pressure buildup results in failure of the case.

Clearly, survival of these cells in satellite applications is critically dependent upon temperature extremes experienced in orbit. While thermal balance calculations permit a reasonable estimate of anticipated conditions for initial design purposes, complex thermal properties of satellite skin, structure and active elements make full-scale prelaunch space simulation mandatory. Only in this manner can theoretical results be confirmed and reasonable assurance of reliability in orbit be established. A current technique for conducting such tests will be briefly covered later.

A final example of environmental sensitivity is presented on Figure 6. Here we have shown the effect of broad-band random vibration on contact continuity of a relay, assuming a white spectrum. G-levels indicated reflect the acceleration at which balance of colinear restraining and inertia forces is achieved for a particular relay. The significant attribute of these data lies in the steepening gradient in sensitivity to the white noise environment, with increasing degrees of environmental mismatch. Again, the necessity for early determination and application of environmental knowledge as vital adjuncts to product design and development, is clearly implied.

FORESIGHT VERSUS HINDSIGHT

In the following, we will touch upon two simulation problems of current importance, and give limited detail on how these have been handled in recent programs. It is well to point out that both of these examples involve environments for which laboratory simulation offers vital information at total costs at least an order of magnitude less than a single launch. Further, vital information generated in flight is normally inaccessible at the moment of generation, and is frequently irretrievable after flight termination.

A Technique in Space Simulation

Our first example involves space-environment simulation, in which significant strides in method have been made during the past two years. It is not intended to review this history, but rather to describe in brief a simple and relatively inexpensive experimental technique for thermal-vacuum testing, which is being applied successfully in the Telstar Communications Satellite program. The problem is to determine thermal-balance properties and evaluate operating characteristics of the satellite under the varying conditions of illumination and internal dissipation which will be experienced in orbit. To do this, we need an energy source, an energy sink and a non-convective environment.

A cutaway view of the test facility being used in this program is presented on Figure 7. The workspace is a cylinder 4.5 feet in diameter and 8 feet long, bounded by a high-emissivity stainless-steel shroud, which is cooled to approximately $-300^{\circ}F$ by liquid nitrogen. Simulated solar illumination from three carbon arc lamps, each with a 420-watt condensible beam possessing desired spectral properties, is introduced through pyrex windows in the rear wall. Pressures in the range of 10^{-6} mm Hg are maintained by a 16-inch diameter oil-diffusion pump. Provisions have been made for supporting and slowly rotating the satellite in four orientations, with instrumentation leads feeding through vacuum-tight terminals in the shaft end-plate. Slip rings have been avoided by programming rotation in two directions, with sufficient slack in the leads to accommodate several turns each way. Illumination is monitored by an array of three 1 x 2 cm solar cells positioned about 6 inches in front of the satellite.

Ideally, energy density and spectral distribution of the incident beam should correspond to the sun's rays in near-space. Similarly, absorptive properties of the heat sink and its temperature should match as closely as possible, the cold, spectrally-black qualities of space. Earth's reflected energy (albedo) and infrared radiation must also be considered as energy contributors, and molecular mean-free-path in the test area must be high enough to permit neglect of air-conductive and convective heat-transfer modes.

The latter requirement is satisfied by pressures in the range of 10^{-5} to 10^{-4} mm Hg, readily obtainable in this facility using conventional vacuum techniques. In attempting to fulfill the other requirements, however, varying degrees of design compromise have been dictated by a combination of program urgency and state-of-the-art limitations. Fortunately, the required compromises are theoretically and experimentally accountable or can be shown to have relatively minor effects on thermal test results.

The main problem involves energy reaching the satellite from secondary sources. If the internal shroud surfaces were non-reflecting (absorptivity = 1) and at a temperature of $4^{\circ}K$ (interstellar space), the satellite would receive only direct radiation from the arcs. Since these conditions cannot be achieved, secondary energy is received by the satellite from arc-light reflection, infrared reflection, and infrared emission from all visible surfaces. To account for energy from these secondary sources, a black shell of the same external dimensions as the satellite, and possessing predictable thermal properties in space, has been used as prime reference in evaluating and programming arc-lamp illumination. Since lamp operation is limited to a fairly narrow power range, rate of energy input is controlled by varying the number of lamps in service at any given time. This can be done without degrading the experiment, since thermal time constants of the satellite are sufficiently long to filter out the effects of any short-term variations in illumination.

Simulation of Missile Flight-Vibration Environment

As our second example, we will consider simulation of the missile flight-vibration environment. Since the primary sources of vibration in a missile are the propulsion system and aerodynamic excitation, this environment can in most cases be considered random. A Gaussian model with mean zero is assumed for vibratory accelerations, and the vibration environment at a particular station is characterized by power spectra.

In practice, simulation of the random-vibration environment is normally achieved by driving an electrodynamic vibrator with the amplified signal from a white-noise generator, band-limited, and clipped at 3 sigma. An array of variable-Q, variable-bandwidth filters is used to shape the driving spectrum to achieve flat frequency response of the highly-reactive moving element with mounted test specimen, a process subsequently referred to as equalization. The filters may also be used to provide varying acceleration density in selected bands of the response spectrum.

Two rather serious limitations are imposed by using a white-noise generator in attempting to simulate the flight vibration environment. First, with the filters mentioned above, it is extremely difficult to achieve any reasonable correlation with power spectra measured in flight. Second, with this approach there is no way of handling variations in power spectrum with time of flight.

An alternative approach is to drive the vibration exciter with data signals recorded during actual missile flights. The value of such a procedure is, of course, dependent upon the quality of the data recorded in flight, and upon the selection of an appropriate fixture for mounting

the test specimen. In vibration-data acquisition, we have found that airborne magnetic recorders offer important advantages over telemetry, especially in the areas of channel availability, data frequency capability, dynamic range and inter-channel distortion. Use of such recorders should be considered whenever recovery is feasible. With regard to fixturing, it has been recent practice to employ a portion of the actual missile structure in laboratory tests, and thereby introduce mechanical-impedance properties of the flight vehicle in some degree.

To evaluate this technique, we have conducted such tests on a missile guidance package, using vibration data obtained with a recoverable airborne magnetic recorder. A missile nose section approximately 7 feet long, with guidance package installed, was mounted in the thrust direction on a 15,000-pound-force vibration exciter (Figure 8). Sensing instrumentation, consisting of piezoelectric accelerometers, was arranged to correspond with the flight configuration. The flight-vibration signal recorded in thrust at the missile parting flange (mounting plane in this experiment), band-limited to 2 kc, was used to drive the exciter. Vibration response was recorded in both the driving plane and the guidance-mounting plane.

Results of this experiment are plotted on Figure 9. The power spectra were obtained by digital analysis based largely upon Reference 2. The data show reasonable agreement between laboratory and flight spectra at the missile parting flange, with moderate deviations attributable to equalization tolerance (± 3 db), system non-linearaties, and vibration-amplifier gain setting. Flight and laboratory spectra at the guidance-mounting rib, however, appear to bear little relation to each other. Clearly, differences in the character of excitation sources and structural transmission paths are responsible for this. In particular, absence of aerodynamic forces and associated effects on structural static loads and dynamic response, raise serious doubts as to the merit of using vehicle structure in laboratory vibration tests on missile-borne equipment.

These results strongly suggest that a preferred technique would employ flight data recorded at points on or adjacent to mounting lugs for equipment of interest, to drive such equipment in the laboratory through rigid fixtures. It is of interest to note that we have applied this latter technique in recent evaluations of gyro performance in the flight vibration environment.

CONCLUSION

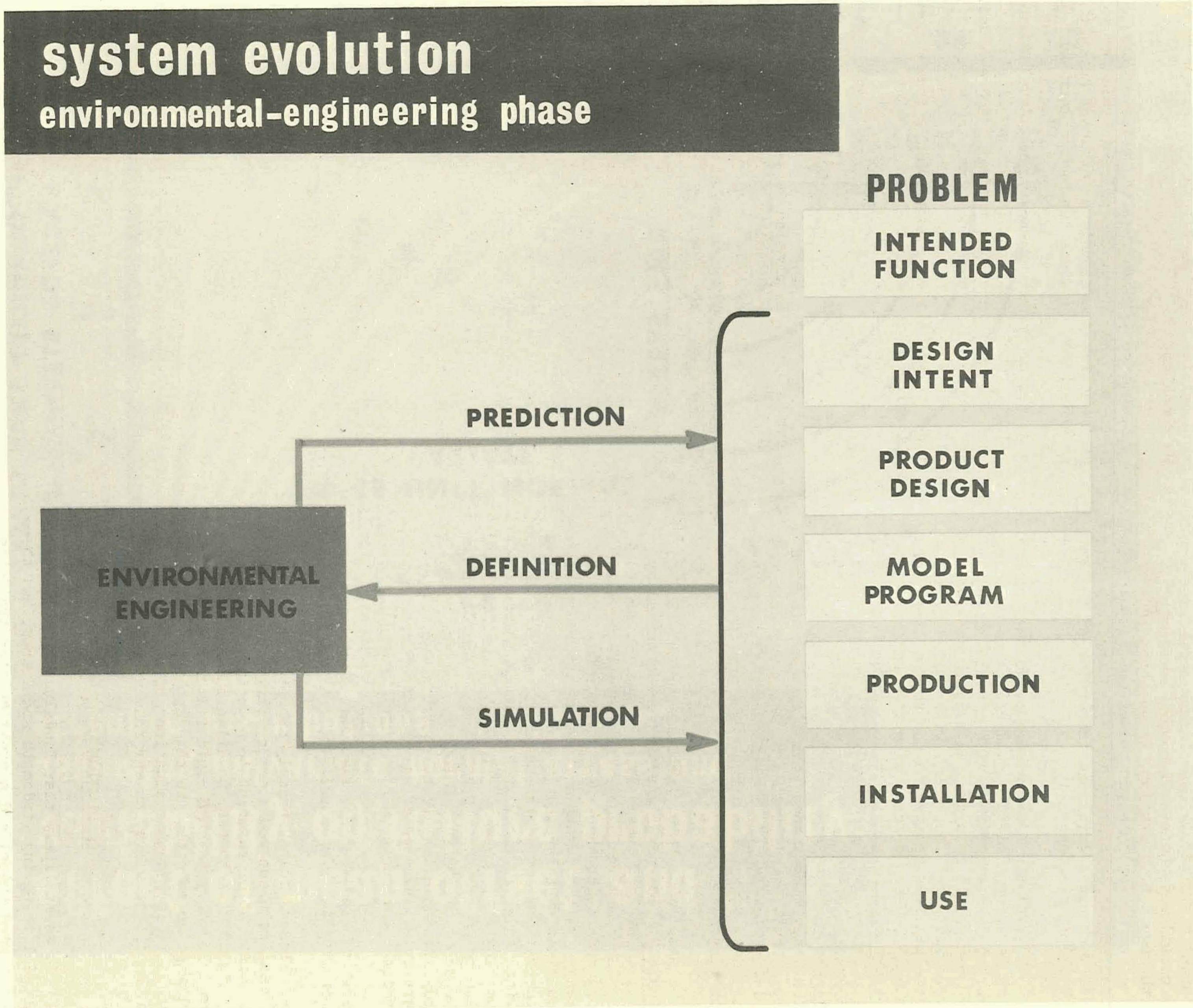
It seems likely that Daedalus might have imparted life-saving wisdom to son Icarus, had there been a wind tunnel and a sun simulator available for pre-flight demonstration. One wonders, of course, whether the Greek Engineer was technically equipped to define the environments of interest, and to evolve a suitable experimental plan for the occasion. This is probably academic, however, since he was in too big a hurry to bother with such details anyway. But must it always be so? We think not.

Failure is sometimes the price of knowledge. More often, however, the price is paid for information already available or at least accessible at modest cost. Since the environment must ultimately be reckoned with, then its definition is a matter of utmost urgency in any development effort. Continued updating and application of environmental knowledge in design and evaluation are essential factors in minimizing wasted time and effort, two priceless commodities in today's market. Is this not, after all, a common goal of all reliability effort?

REFERENCES

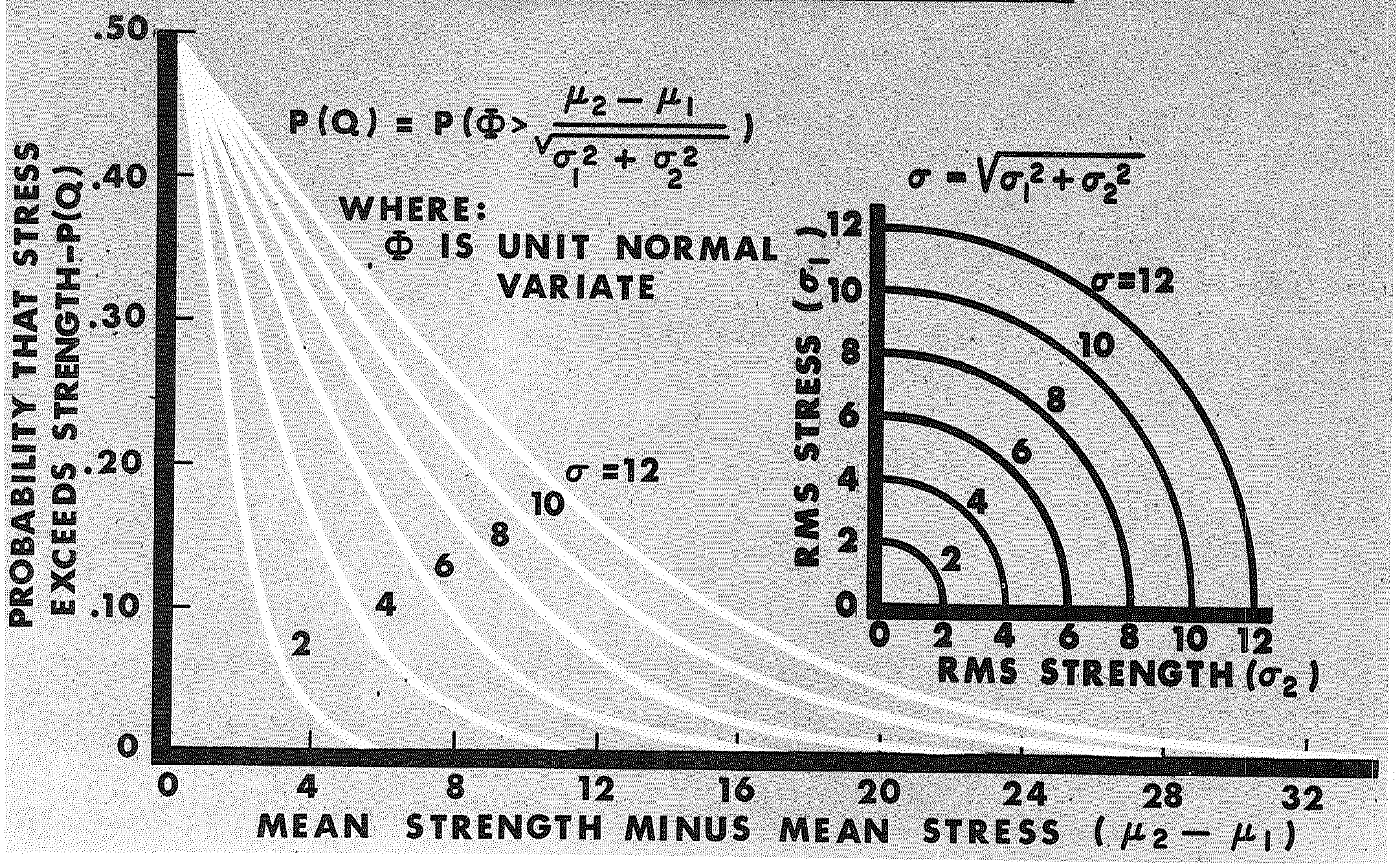
Norman, J. E., Estimating Reliability as a Function of Stress/Strength Data, ARGMA, November 1961.

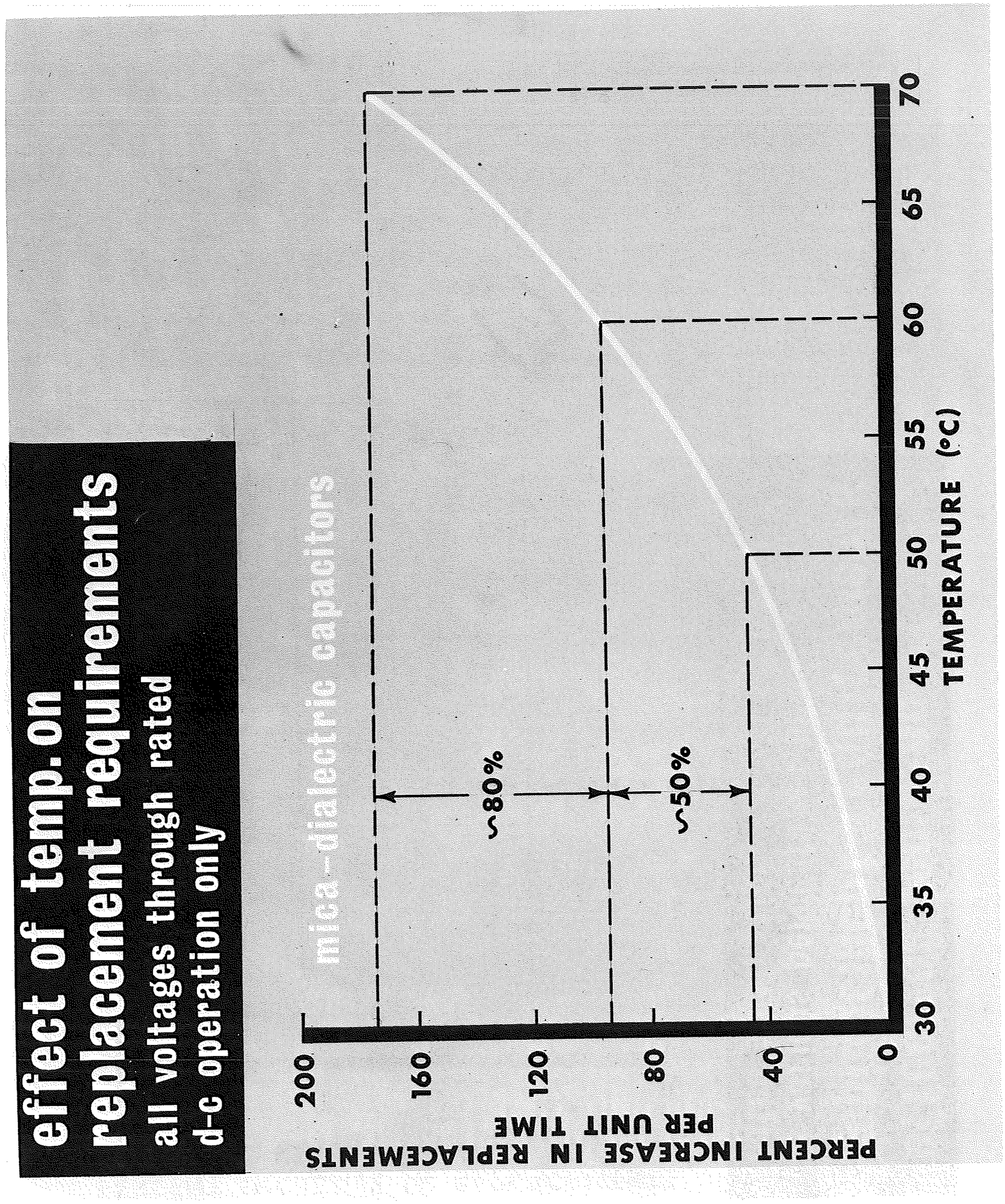
Blackman, R.B. and Tukey, J. W., The Measurement of Power Spectra, Dover, 1959.


system evolution
environmental-engineering phase
PROBLEM
INTENDED FUNCTION
DESIGN INTENT
PRODUCT DESIGN
MODEL PROGRAM
PRODUCTION
INSTALLATION
USE
PREDICTION
DEFINITION
SIMULATION
ENVIRONMENTAL ENGINEERING

effect of mean offset and variability on failure probability

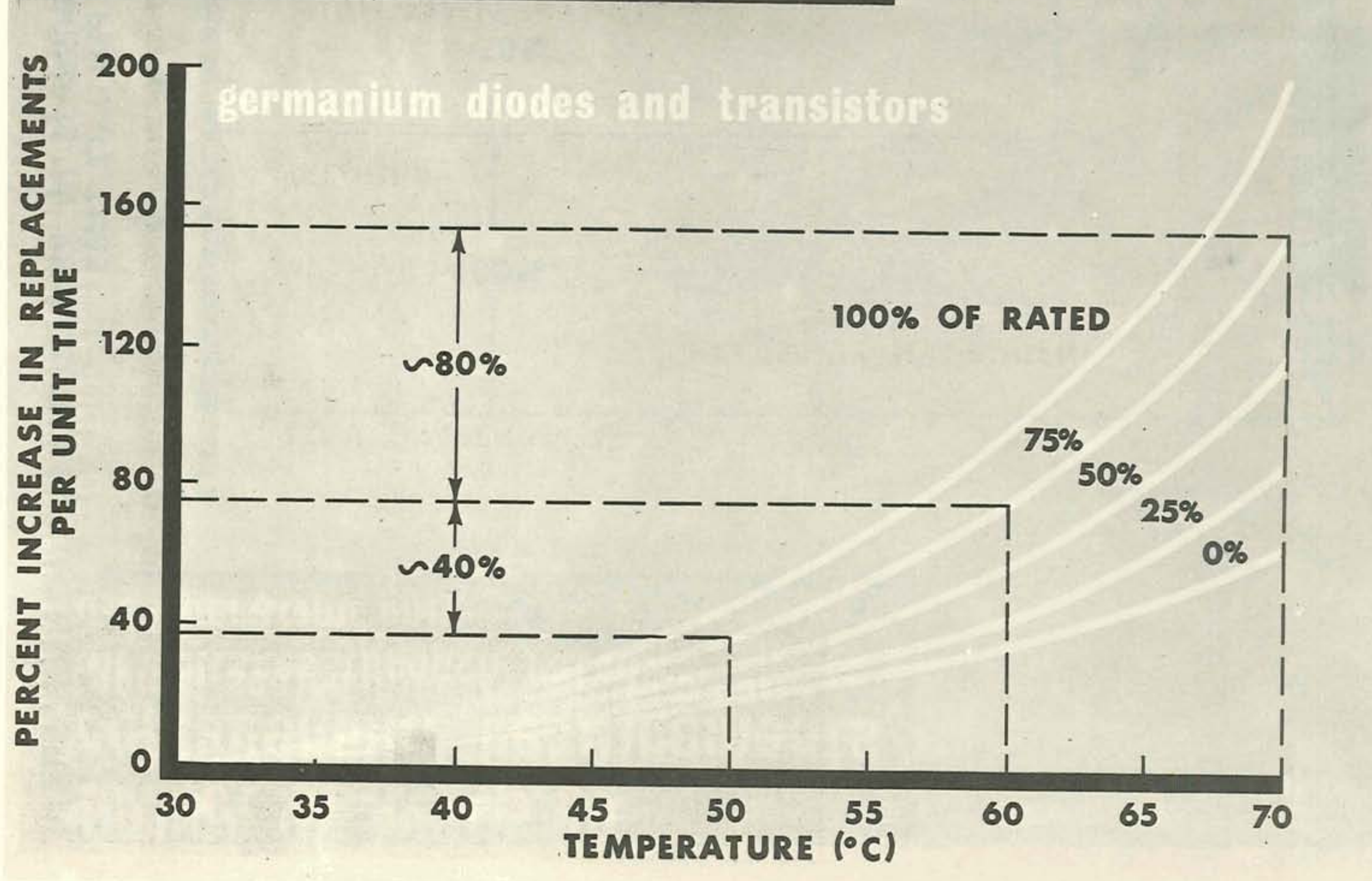
assuming univariate normal stress and strength distributions

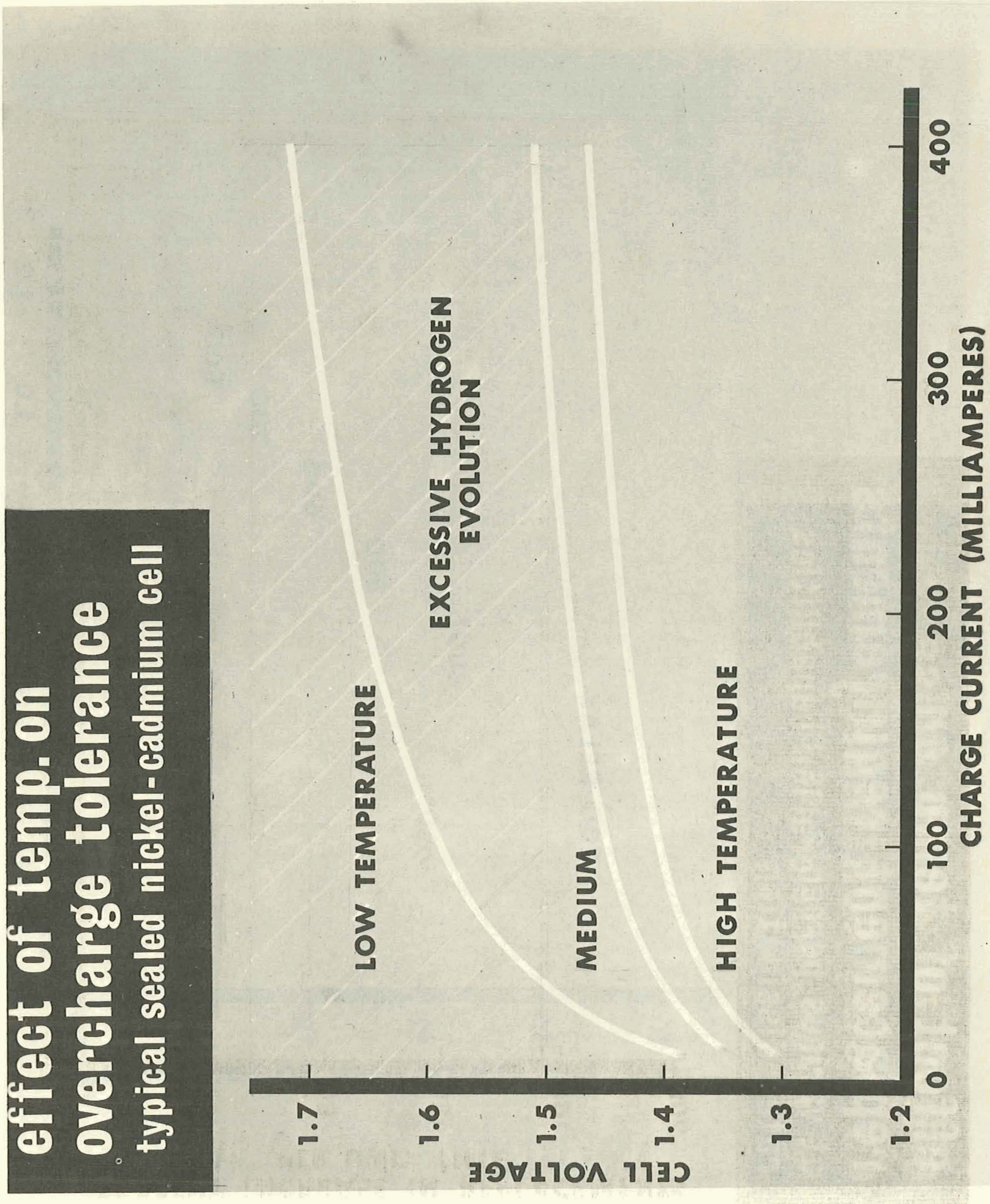


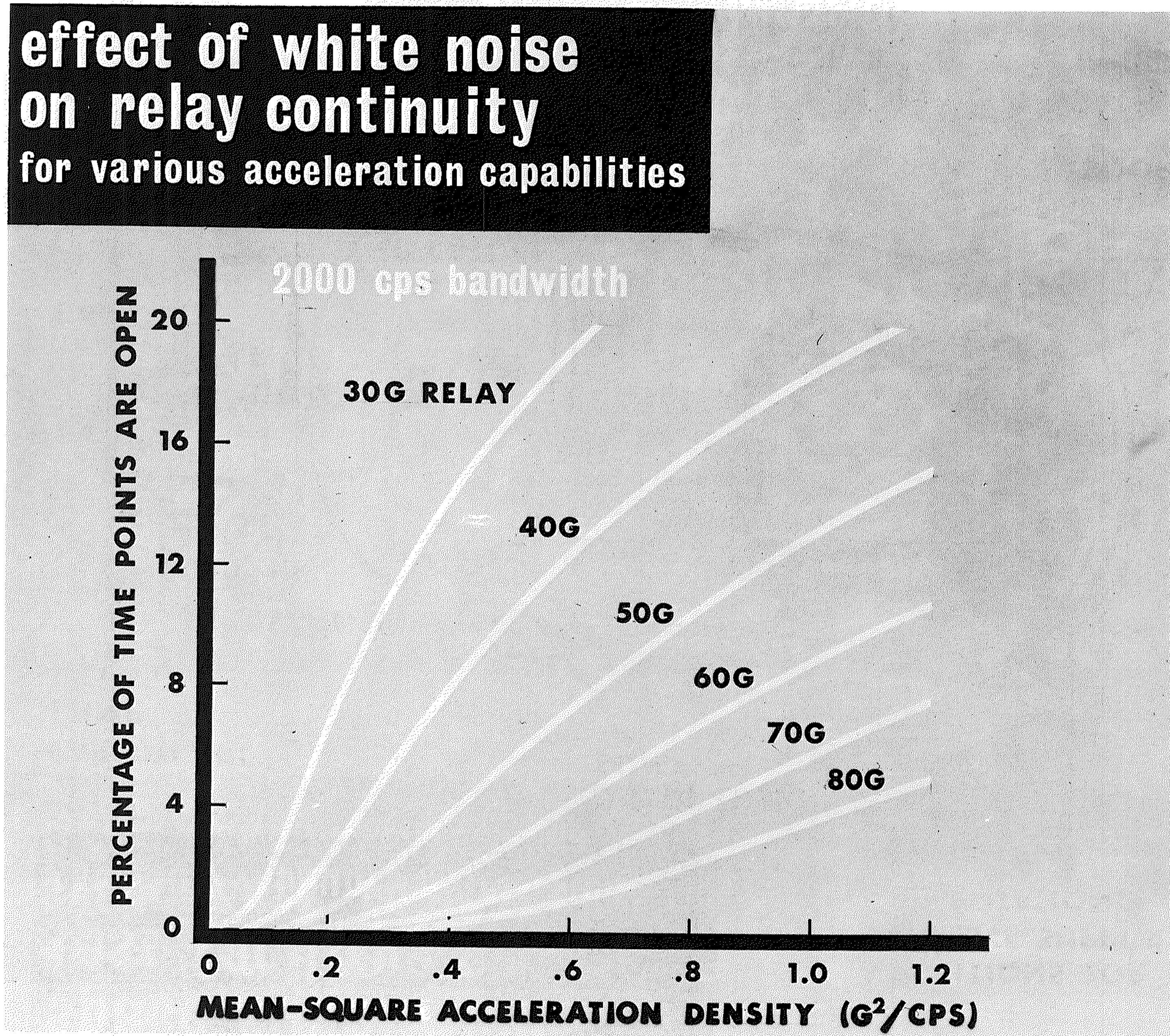

effect of temp. on
replacement requirements
all voltages through rated
d-c operation only
mica-dialectric capacitors
~80%
~50%
PERCENT INCREASE IN REPLACEMENTS
PER UNIT TIME
200
160
120
80
40
0
30
35
40
45
50
55
60
65
70
TEMPERATURE (°C)

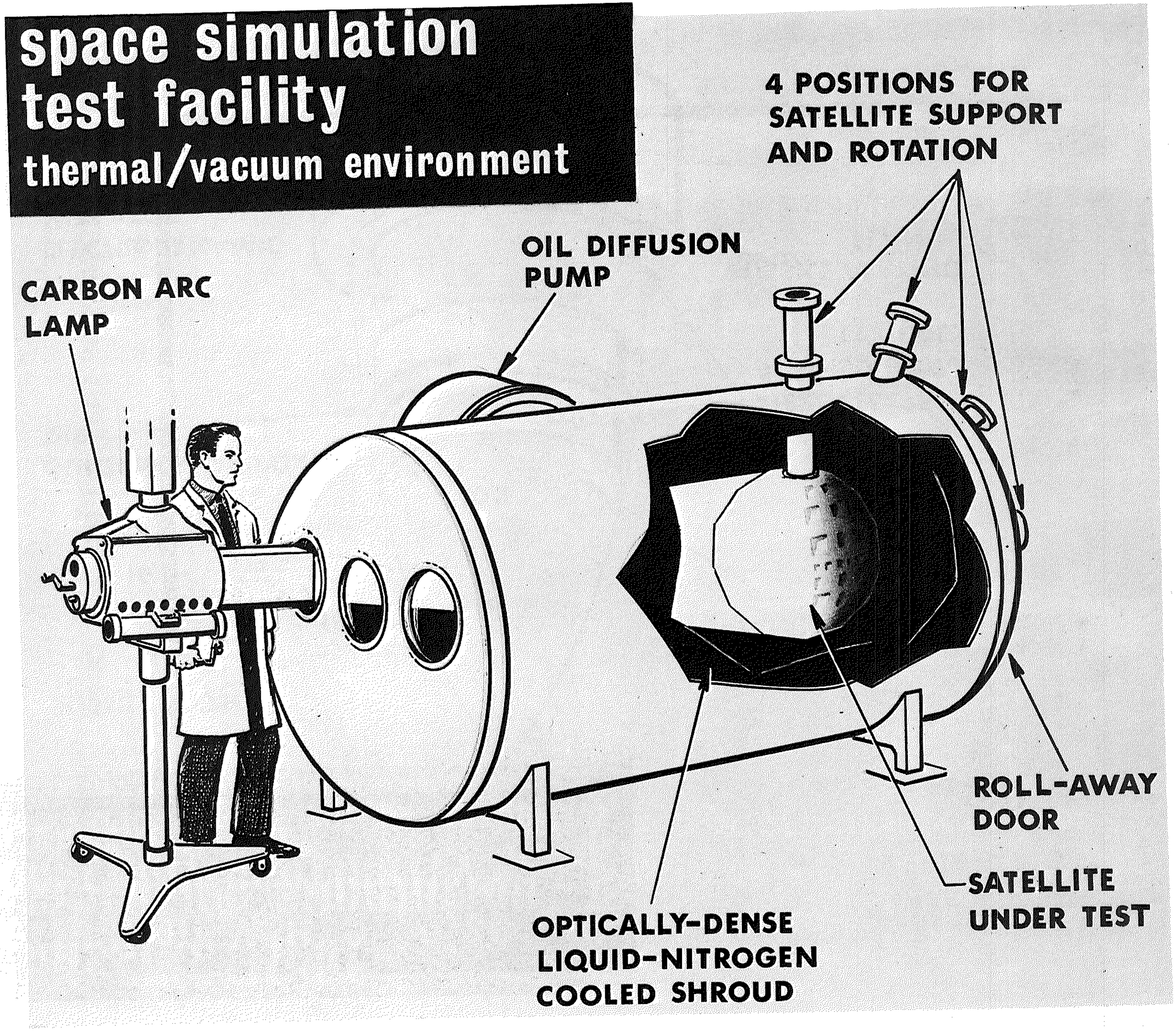
effect of temp. on replacement requirements

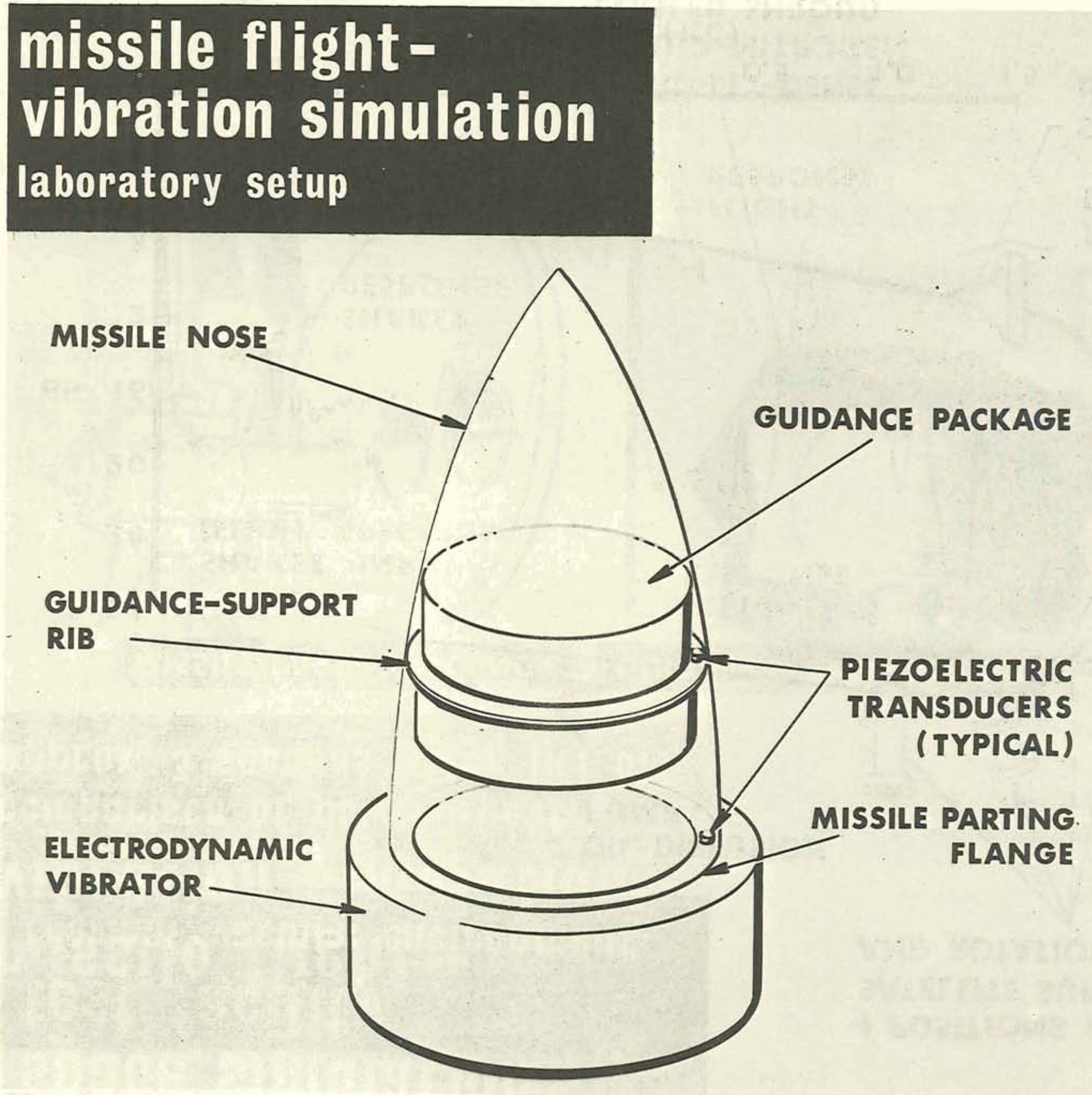
at various percentages of rated dissipation

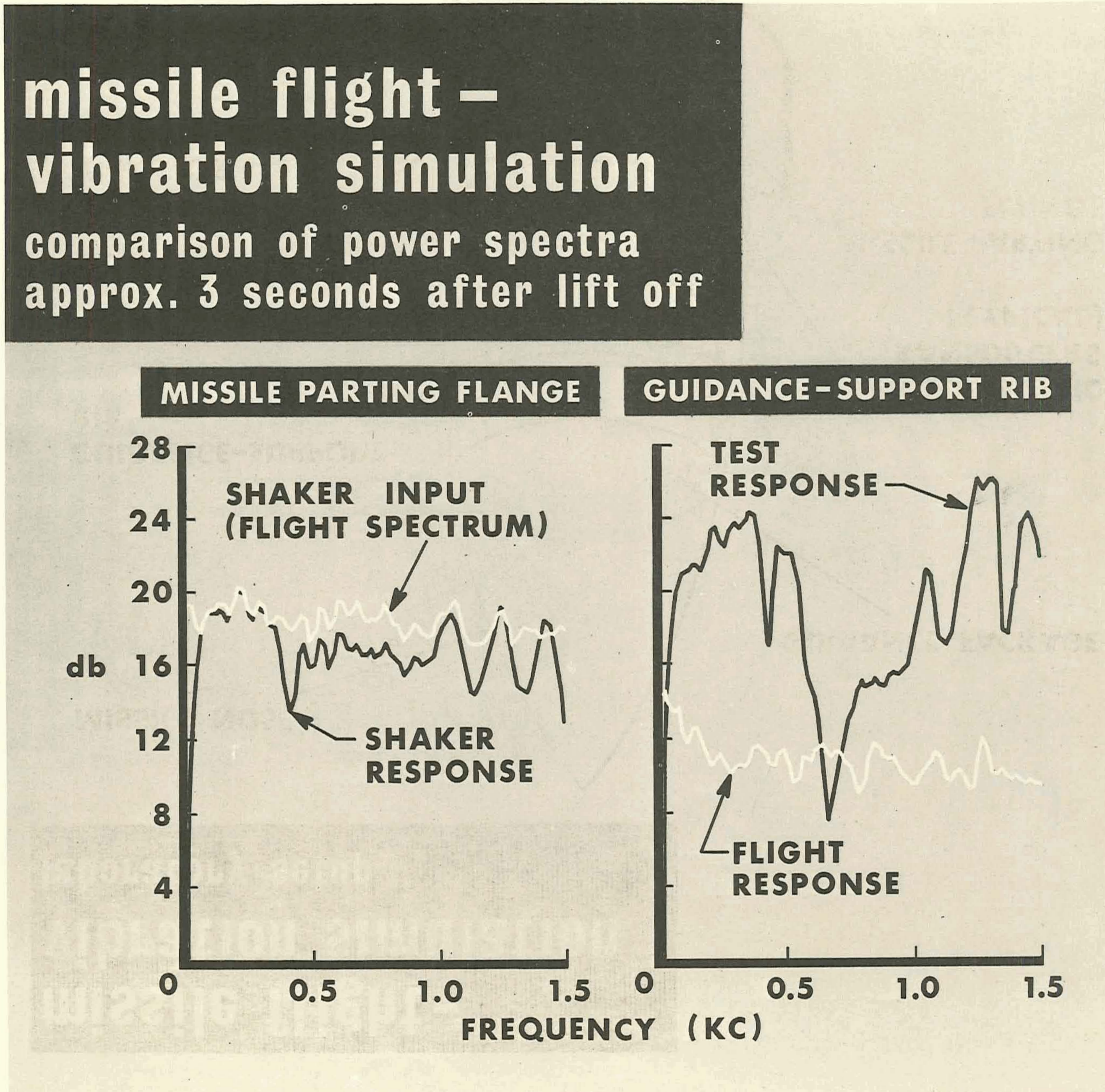



effect of temp. on
overcharge tolerance
typical sealed nickel-cadmium cell
CELL VOLTAGE
1.2
1.3
1.4
1.5
1.6
1.7
0
100
200
300
400
CHARGE CURRENT (MILLIAMPERES)
LOW TEMPERATURE
MEDIUM
HIGH TEMPERATURE
EXCESSIVE HYDROGEN
EVOLUTION


effect of white noise
on relay continuity
for various acceleration capabilities
2000 cps bandwidth
PERCENTAGE OF TIME POINTS ARE OPEN
20
16
12
8
4
0
30G RELAY
40G
50G
60G
70G
80G
0
.2
.4
.6
.8
1.0
1.2
MEAN-SQUARE ACCELERATION DENSITY (G²/CPS)


space simulation
test facility
thermal/vacuum environment
4 POSITIONS FOR SATELLITE SUPPORT AND ROTATION
OIL DIFFUSION PUMP
CARBON ARC LAMP
ROLL-AWAY DOOR
SATELLITE UNDER TEST
OPTICALLY-DENSE LIQUID-NITROGEN COOLED SHROUD


missile flight-
vibration simulation
laboratory setup
MISSILE NOSE
GUIDANCE PACKAGE
GUIDANCE-SUPPORT
RIB
PIEZOELECTRIC
TRANSDUCERS
(TYPICAL)
MISSILE PARTING
FLANGE
ELECTRODYNAMIC
VIBRATOR


missile flight –
vibration simulation
comparison of power spectra
approx. 3 seconds after lift off
MISSILE PARTING FLANGE
GUIDANCE-SUPPORT RIB
28
24
20
db 16
12
8
4
0
SHAKER INPUT
(FLIGHT SPECTRUM)
SHAKER
RESPONSE
TEST
RESPONSE
FLIGHT
RESPONSE
0.5
1.0
1.5
0
0.5
1.0
1.5
FREQUENCY (KC)

17295

SYSTEM RELIABILITY EVALUATION FROM SUCCESS AND FAILURE DATA

R. Hammell
Bell Telephone Laboratories, Incorporated
Whippany, New Jersey

It has been estimated that man may have occupied this planet for two billion years. During all but a fraction of one percent of this very long time, his upward progress has been slow, indeed. Gradually, man learned that he must use the ideas, discoveries and experiences of others as stepping stones toward his distant goal. When the total amount of recorded knowledge had reached a necessary level, man's rate of achievement began to climb in exponential fashion.

Today, we are recording such vast amounts of information that we are at a loss to sift the useful from the useless. And the problems of retrieving needed material are often so great that we are in danger of either having to rediscover or to do without.

In the reliability field, we seem to have reached the point where each practitioner must make a painful compromise between trying to do his job and spending every waking moment studying the tidal wave of material crossing his desk. If we can only bear it for just a little longer, I believe that there is much promise of improvement. Before any complex field of endeavor can become a "science, it must first be an "art". Our dilemma stems from the fact that reliability is in transition between these two states.

Earlier this year, at the Reliability and Quality Control Symposium in Washington, and at the IRE Convention in New York, we were impressed by men who had become engineers and then pursued the study of medicine. One man is using his medical knowledge in space engineering research; another is using his engineering to solve urgent data recording and correlation problems in the medical world. Both men should open some very important doors. This is always to be expected when various intellectual disciplines are deliberately mixed.

All this suggests that the cooperation between systems designers, equipment designers, component designers, human factors engineers and reliability engineers should be tightened.

There follows an attempt to examine some of reliability's developing vocabulary, to identify the kinds of information we must collect during a system's evolution, and what we must do with it. A "balance sheet" will be presented, to show what we get and what we pay for correcting troubles detected in each successive developmental stage.

First, let us look at some of our specialized language. Let us examine some of the words used in this series of papers, to see which ones have specific meanings and which may have meanings that depend upon one's viewpoint.

What do we mean by the words "field" and "user"? Clearly, this depends upon where we stand. To the military equipment manufacturer, the only proper concept of a product's being "in the field" should be that the product has been delivered into the hands of the ultimate user, the military operator working under tactical conditions. Unfortunately, there are too many manufacturers who believe that their equipment has reached this stage when a prototype has passed its performance tests and the customer has paid the bill. As we hope to demonstrate, there are serious dangers in the latter attitude.

The component manufacturer, in contrast with the equipment manufacturer, may feel that his product is "in the field" as soon as he has shipped it to the equipment manufacturer. From where he stands, anyone who handles (or mishandles) his product is a user. His component actually may be exposed to worse conditions during equipment development than in any other stage.

How about the word "system"? Very few systems consist only of hardware; most systems use men as essential components within closed feedback loops. No man-machine system can ever perform at the required level if proper attention has not been paid to the limitations, needs and capabilities of the human components. As mission times become very short and as tactical areas expand, weapons systems are required to operate ever faster. This requires that astronomical amounts of data be collected, assessed and used to produce exactly right decisions with blinding speed, and that men must be eliminated as direct functional links.

Eliminated from system functions, man continues to be essential for monitoring troubles and for employing correct and rapid repair procedures. We must not conclude from this that human factors engineering has lost importance; to the contrary, its importance has never been greater. There is a severe and urgent burden on equipment designers to provide maintenance men with the utmost in trouble detection and correction facilities, and to arrange their

designs for instant and economical repair by very ordinary kinds of men.

The importance of exploiting failure data in any system evaluation is obvious; less obvious is the importance and utility of success data.

For each successful launching by a missile system, it is of vital importance that records be kept of environmental conditions, ground equipment performance, telemetered data from missile, and tracking data if we are to assure the success of future launchings. For once a high degree of system reliability has been achieved, unremitting efforts are required to guard against deterioration.

Data from firings must be compared with data from laboratory testing, to be sure that the "margins" assumed in the laboratory testing, compared to field conditions, are really there. This careful comparison has been made in the use of the Bell Telephone Laboratories' Command Guidance System, designed for TITAN I. This system has been used so far for guidance in over 80 firings of ICBM's and space vehicles, without a single failure of the ground or missile-borne equipment.

Figure 1 shows the evolutionary phases of a typical system, from earliest planning to final, tactical use. It is interesting to consider this from the standpoint of failure reporting and analysis. The following questions come to mind. Which blocks send information to the failure analyst? In which phases can failure analysis pay the greatest dividends? What do the feedback loops look like? Is there any stage at which failure analysis is useless to the project? At what point should we stop analyzing failures from a system?

Trouble Data From Product Design Phase

If a failure analysis program can be conducted during the product design phase, with information from breadboard experiments, great benefits can be realized. There are the maximum opportunities to change to better components and better circuit and mechanical design practices. There may even be time available if better components must be developed. And, of course, changes are inexpensive and do not have big repercussions.

Data From Model Program

It is essential that when an equipment is in the model or prototype stage every trouble, however small, be reported to the reliability organization and that it receive energetic treatment. If the models closely represent the final design, and if they have been built according to the company's typical fabrication processes, most of the troubles should resemble those which might be encountered in final equipment. It is important that the failure analyst's findings be given quickly to responsible project personnel, before the final failure analysis report has been written, printed and distributed. Any effective informal means should be used. The analyst often receives a reply from the project people, stating what they have done in response to recommendations, and includes this statement in his final published report. If all parties have done their jobs properly, this trouble should not recur. In a large project, it is normal to have many design changes resulting from tests of model or ptototype equipment.

Data From Production

It can be expected that the production phase will yield a whole string of new troubles, many of which do not resemble those from earlier phases. Again, it is urgent that failure analysis be done rapidly and that the preliminary findings be transmitted informally.

Troubles occurring in production include

(a) defects in equipment design,

(b) troubles caused by lack of skill in production. These will not result in design changes, but in additional worker training and/or modifications in process instructions.

(c) Those resulting from changes in manufacturing processes,

(d) latent troubles which can appear only after a quantity of units has been built.

(e) the need to select components, by trail and error methods, for proper circuit performance. This may be caused by innocent-looking, but important differences between the construction of models and final units (e.g. wiring layout and methods). It may be due to differences between the production and preproduction versions of certain special components. Or it may indicate that proper circuit operation depends upon an uncontrolled component characteristic.

Data from Installation

If it could be assumed that production equipments are installed in exactly the same way as model and prototype equipments, using the same materials, tools, methods and kinds of men, then most installation troubles should be those caused by errors or abuse. But there will be a need for some additional design changes. The need for some of these changes may be apparent only after production equipments have been handled, packed, transported over long distances, and sometimes stored in a harmful environment, prior to installation.

Data From Use

If a system has been soundly planned and well designed, and if reliability procedures have been exploited to the fullest, there should not be many big troubles in use.

Our decisions and actions at this stage can have a very big effect (for better or worse) on future systems. Remembering that all progress depends upon a study of past experience, we must realize that a trouble-ridden system contains an exceedingly valuable library on what not to do. It is especially important that all in-use troubles be carefully reported and analyzed.

Analysis results will, in many cases, affect future choices and/or applications of certain components and materials, system and equipment design procedures, manufacturing processes and installation methods.

When there has been a lot of in-use trouble, we'd be wise to take a careful and skeptical look at the reliability procedures that we used in the earlier phases. It is possible that we will find something wrong with our chosen reliability tools, or with the way we used them. But there is another possibility; it is that the project organization may not have recognized the importance of our recommendations. The burden is on the reliability organization to arrange feedback or check-up routines so that it will know the consequences of its recommendations. If the project decides that action is unwarranted, the reason should be determined and recorded.

Data Collection

We have talked a lot about the use of trouble data, but have not touched on the problems of collecting it. The "success data" are not difficult to obtain; this is because of their nature and because they are recorded under the control of engineers who are responsible for their use. The problem is most acute in the case of trouble, failure, replacement and readjustment information. How do you motivate a maintenance man so that he will want to give you a complete story? Sometimes we have difficulty obtaining any story, however inadequate.

Much of our most valuable data come from "R&D Field Sites" where the environments and system use conditions might be called quasi-tactical. Perhaps the most successful method we have used for obtaining data is to have an experienced man assigned to each site, with the primary duty of reporting the full story. This man goes to the place on the "reservation" where the trouble occurred, interviews the people who coped with the trouble, looks at their logs and prepares the report. In addition to all the obviously needed information, it is vital that he be specific about

(a) circuit positions of failed, replaced or readjusted components,

(b) whether the replacement or readjustment resulted in cure,

(c) the number of operating hours accumulated on each replaced component, or up to the time when an adjustment was made,

(d) complete statements of symptoms and events of possible significance.

Many failures cannot be analyzed at all unless the amount of time accumulated on a replaced component is given. Of course, this means that the reliability organization must assure itself that the system designers have included enough running-time meters, and that they have been installed in the right places.

On the NIKE-ZEUS project, we had been receiving many failed samples of a certain relay. The contacts looked as though they had been abused electrically but, lacking estimates of the number of times these relays had been operated, we could not make a conclusive analysis. When, one day, one of these relays was accompanied by a statement of the number of operations, it was apparent that it had passed its expected life. The relay was not being overloaded, but it was being operated so often that it would require frequent replacement.

Whatever system is adopted for obtaining field failure data, it is invaluable to use the feedback principle so that the maintenance man knows his report did not fall into a bottomless pit. Send him a copy of your failure analysis report. You then have a vehicle for words of praise for a job well done; and you have the opportunity to do a little complaining if he has let you down.

Failure Analysis

We have heard a great deal about the mechanics of component failure analysis. This art has become well understood and has been thoroughly documented. The important thing to remember is that our study must extend far beyond the failed component (which often turns out to be perfectly good); it is only a part of the story. We must examine where and how it has been used (or abused), how it was housed, how it was applied. We must chart and study the frequencies of troubles according to their positions in circuits. And we must pay heed to those troubles that are corrected only by the changing of adjustments, without component replacements.

Of special interest to the failure analyst is the case in which the trouble disappears when a component is replaced, but no trouble can be found with the removed component. This raises a number of possibilities:

(1) External connections to the removed component may have been faulty.

(2) The removed component may contain an intermittent defect. It may be sensitive

to some quantity such as temperature, moisture, shock, vibration, voltage, or a combination of them.

(3) The circuit design may be marginal, so that it will not work when a component characteristic is near a limit.

(4) Proper operation of the circuit may depend upon some "uncontrolled characteristic" of the component. This is not uncommon.

(5) When no other explanation can be found, it is possible that some other action actually was taken, in addition to replacement of the component. The person who prepared the trouble report may have been unaware of this, he may have forgotten it, or he may not be sufficiently objective to report an error which he may have made.

Priorities

On the Command Guidance System project, the field trouble report cards have a space for indicating whether the effect of a trouble on system functioning was "critical," "major" or "minor." The terms are self-explanatory. Special efforts are made to give priority attention to the critical cases. When the analysis groups are overloaded, minor items are deferred until the work load drops.

On other projects, degrees of severity are not usually indicated. All cases are handled, in the order of arrival, as being of equal importance. However, our Systems Reliability Department keeps a box score on each type of trouble and, from time to time, issues requests to the analysis groups to pay special attention to certain cases, or to stop analyzing other kinds of troubles which have become well known and are receiving corrective action.

Conclusions

1. Reliability is in transition between art and science. Greater efforts are needed to mix it with other disciplines.

2. To increase understanding by project people, let's not be reticent about our success.

3. We must give balanced attention to success and failure data and use both of them as tools.

4. Failure analysis pays the greatest dividends when done in the earliest equipment design stage.

5. <u>All</u> troubles should be reported from <u>all</u> phases of a system's life, including field use.

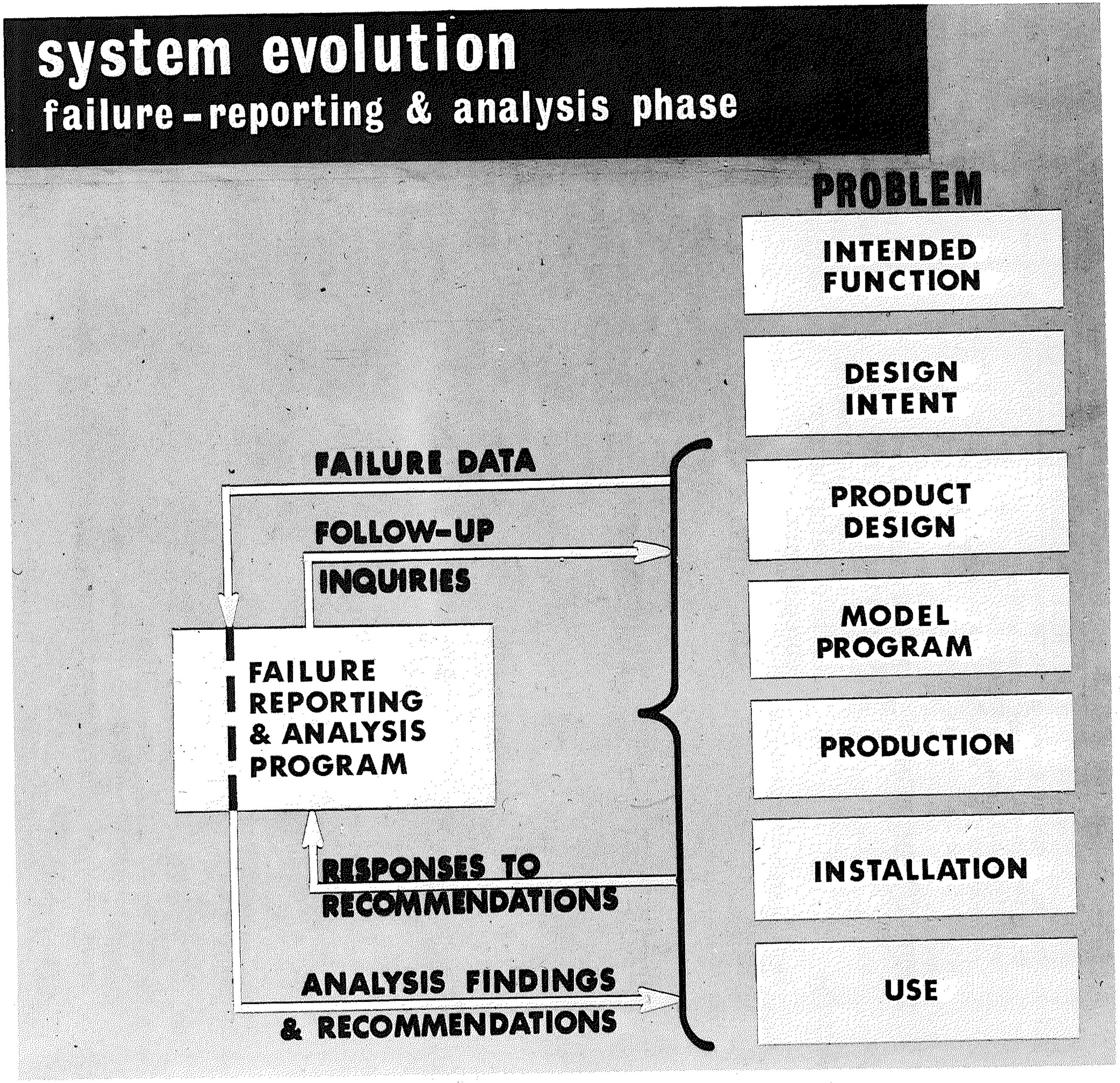
6. Analysis of in-use failures is vital to the greater reliability of future systems. If we do not do this, we shall never stop committing the same old errors.

7. If the demonstrated reliability of a system falls far short of predictions, we must look carefully at the tools we used, and the way we used them.

8. Collection of trouble data is not easy.

9. Component failure analysis must go far beyond a mere study of the component.

10. Effort expended in failure analysis should be in proportion to the effect of the trouble on the system's main mission.


system evolution
failure-reporting & analysis phase
PROBLEM
INTENDED FUNCTION
DESIGN INTENT
PRODUCT DESIGN
MODEL PROGRAM
PRODUCTION
INSTALLATION
USE
FAILURE DATA
FOLLOW-UP INQUIRIES
FAILURE REPORTING & ANALYSIS PROGRAM
RESPONSES TO RECOMMENDATIONS
ANALYSIS FINDINGS & RECOMMENDATIONS

Balance Sheet on Failure Analyses Performed in Various Phases of Project

	Savings	Costs
PRODUCT DESIGN	Model changes. Opportunity to modify basic design approach, or to develop better components.	Failure Analysis. Design changes (relatively slight cost).
MODEL	Manufacturing Changes	Failure Analysis. Design changes (moderate cost).
PRODUCTION	Field changes	Data Collection. Failure Analysis. Retraining. Design changes (expensive). Process changes.
USE	Improved reliability of future systems.	Data Collection. Failure Analysis. Field changes (very expensive). Design & Production changes.

Figure 2

A SURVEY OF TECHNIQUES FOR ANALYSIS AND PREDICTION OF EQUIPMENT RELIABILITY

by

H. Elmore Blanton
Raytheon Company
Lexington, Mass.

Richard M. Jacobs
Sylvania Electric Products, Inc.
Waltham, Mass.

17296

Summary

This paper presents a brief synopsis of representative techniques that are used in the analysis and prediction of equipment reliability during the design phase. In particular, attention is directed to: (1) techniques commonly employed for the prediction of circuit or module reliability, given part reliability, circuit configuration, and environment; (2) techniques commonly employed for the prediction of equipment (or systems) reliability, given module reliability, equipment configuration, and operational and environmental requirements; and (3) advanced statistical techniques which are useful under certain conditions to supplement those techniques previously mentioned.

Introduction

Techniques useful in the analysis and prediction of equipment reliability have developed rapidly during the past several years. Concurrently with this development, emphasis has been placed on the accumulation of failure-rate data on parts and the measurement of reliability of existing equipments in order to provide numerical significance to the various mathematical expressions used in describing reliability. These efforts have been accelerated by an increasing recognition of the value of applying an analysis and prediction technique during the design phase. Consequently, reliability engineers, and others in related activities, have been confronted with an ever-increasing number of "best" techniques for analyzing and predicting equipment reliability.

Under these circumstances, it became apparent that a survey of these techniques would prove valuable provided the survey elaborated on the recommended uses of a technique, its distinguishing features, and the sources of data. This paper is an effort to present such a compendium of information. No attempt has been made to evaluate, recommend, or criticize the methods or techniques either by the sequence of the presentation or by the descriptive details.

Currently available techniques are classified in this paper according to application:

(a) Prediction of circuit or module reliability when part reliability, circuit configuration, and internal and external stresses are given (discussed in Section 2);

(b) Prediction of equipment or systems reliability when module reliability, equipment diagram, and operational requirements are available (Section 3);

(c) Advanced mathematical/statistical techniques which supplement the preceding methods under certain prescribed conditions (Section 4).

A few techniques which do not fall into these categories but which may prove valuable for specific applications are noted in Section 5. The ways in which these various methods may be employed, as well as an indication of their validity, is examined in Section 6.

Reliability prediction as considered here includes all methods used in obtaining a numerical indication of the inherent reliability of the device, regardless of whether that numerical indication is intended as a measure of conformance to specifications, a means for comparing similar devices, or for other purposes. The terms "part," "module", and "equipment" are used to represent the basic elements of a device, a collection of those elements which function together as a unit, and the final assemblage of those elements as required to accomplish a specific task, respectively.

A literature search reveals that although a few papers on reliability prediction appeared during the 1940's, the bulk of the material was published subsequent to that time. The authors have reviewed personally over 200 references. The bibliography at the end of this paper lists those papers which have been cited in the text as well as others which may be of general interest. Also included are references to several edited bibliographies which may be consulted for information on additional papers. (References 1, 2, 3, 4, 5, 6)

Prediction of Module Reliability

The prediction of electronic circuit or module reliability has been the subject of many papers; however, essentially all of these papers discuss the use of the basic technique of obtaining the module reliability from the summation of the failure rates of the constituent parts. Appropriate formulas may be applied to account for the series or parallel configuration of the parts which compose the module. The points of

disagreement between the papers are what numerical data should be used for the failure rates and the degree of detail that should be considered in defining the failure rates. Several short cuts and refinements in module prediction techniques have been discussed. Most of the papers relate to electronic equipment - the extension to non-electronic equipment may be reasonably straightforward if the appropriate numerical data are available.

Mathematical Models for Module Reliability

One of the earliest attempts to predict reliability for electronic equipment was made shortly after World War II. Based on experience with World War II equipment (C2, D1, H1), it was determined that the several ways in which equipment could fail are: (1) frequently repeated failures caused by parts either poor in quality or overstressed, (2) randomly occuring failures, (3) degradation failures of various parts. It was thought that frequently repeated failures could be rectified by retrofits, and the degradation failures could be prevented by appropriate maintenance practices. At that time, however, methods to reduce the random failures were not known. The data gathered indicated a total failure picture which could be approximated by the exponential law and established the fact that the probabilities of survival for the equipments were influenced by the complexities. To predict the magnitude of failures in equipment, typical failure rates for various part types were established. These failure rates, multiplied by the number of parts in the equipment, were shown to yield an estimate of equipment reliability. This basic technique encompasses the concepts of many of the more elaborate methods in use today.

As an extension to this early work, the ematical model giving the failure rate of ... module as the summation of the failure rates of the constituent parts has received wide acceptance. The reliability of the module, in turn, is computed from $R = e^{-\lambda t}$ where λ is the failure rate of the module.

The use of this mathematical model implies the acceptance of certain basic assumptions:

(a) All parts are considered to be functionally independent, that is, a failure of any one part will not affect the probability of failure of any other part.

(b) The successful functioning of each and every part is required for the successful functioning of the module

(c) Failure-rate data for the various parts are available

(d) The parts experience constant failure rates during the period of module operation and hence the exponential distribution is applicable.

The validity of these assumptions with respect to the module being studied should be considered in order to avoid gross errors. Recent work has shown, for example, that the assumption of constant failure rates and the exponential distribution may not be acceptable in all instances. Work is underway to determine the applicability of the Weibull, Gamma, Log Normal, Poisson, Binomial and normal distributions to various elements of the over-all problem. As additional data become available, confirmation of the validity of particular distributions in describing the reliability to specific parts and modules may be expected.

Part Failure-Rate Data

The principal distinction between methods reported for the prediction of module reliability is the part-out-failure-rate data employed. It is recognized that failure rates vary considerably due to the environment of internal and external stresses. These stresses are derived from the way in which the part is used in the module, the way in which it is mounted or packaged, the ultimate use of the module, and operational procedures such as on-off cycling. In addition, failure rates vary as results of inherent design of parts, conditions of manufacture and other factors.

In using published failure-rate data, the source of the data must be carefully considered. For example, if it is obtained from field experience with shipboard equipment, it may not be directly applicable to airborne equipment or to fixed ground-based equipment. Furthermore, in certain compilations of data, failure rates were obtained directly as a function of the total field removals including preventive maintenance actions; whereas, in other instances, data supposedly resulting from human error, secondary failures, and/or other extraneous sources of malfunction were removed before the computation of failure rates. Failure-rate data also are available from extensive parts-testing programs conducted either by parts manufacturers or parts users; but insufficient time has elapsed to permit high confidence correlation of the results of these tests with field data to establish the validity of the test programs. Other failure-rate data are computed from parts-test data combined with controlled or uncontrolled field data.

Under these circumstances, each user must apply caution in selecting the data to be employed in his particular prediction. Currently, insufficient information is available to permit the selection of a "best" source of data - the choice must be made in view of the requirements of the particular prediction program.

The earliest sources of failure-rate data, of course, provided indications of only nominal failure rates for broad categories of parts. As the collection of failure rates has continued through the years, these data have been refined; and, currently, compilations provide many breakdowns into various categories of parts as well as indications of the effects of various stresses. The exact manner in which reliability is related to stress level varies considerably.

One compilation of failure-rate data, which was updated recently, was drawn from shipboard applications (S7, V1, V2). This source presents single failure-rate numbers for the majority of part categories. In the case of tubes, transistors, resistors, capacitors, and several other commonly used electronic parts, graphic data are provided to permit a modification of the basic failure rate in terms of the severity of the application, measured as a function of the principal electrical parameter affecting reliability. The effects of other environmental factors are not considered. Data in this form are useful in obtaining initial estimates of module reliability, before information is available on the particular environmental stresses to be encountered.

Perhaps the most widely used source of failure-rate data (R3, R4, R8, R11) extends the concept of application severity levels to provide charts and tables where failure rate is shown as a function of the principal electrical stress on the part and the principal external stress, usually ambient temperature. Information presented in this form is particularly valuable as the design progresses and becomes firm. It provides the designer an opportunity to study trade-offs between reliability and ambient temperature, electrical stresses on the parts (which when interpreted as per cent of rated stress often may be related to the size of the part) maintenance factors, cost and other related considerations. These particular data reportedly are derived from laboratory and field tests of fixed station ground-based equipment together with theoretical considerations. It has been proposed that failure rates obtained from this source be modified by multiplying by an appropriate factor in the range from 1 to 80 to account for the severity of the application environment (i.e., ground based, manned aircraft, missile, etc.)(D4).

The use of adjustment factors, often called "K" factors, to modify basic failure rate data also is recommended in several publications. In one of these (A3, B20), the "K" factors are used merely to modify basic failure rates to account for certain circuit stresses; for example, the ratio of actual to rated voltage, temperature above recommended ambient, or on-off cycling. In another (H10), the "K" factors are used to account for use environment as well as other factors which are not directly reflected in the tabulations of basic failure rates.

Another tabulation of failure data (E2, E3, E4) provides a table of nominal or generic failure rates and application factors which are functions of both circuit and use environment. In the tabulation of failure rates, both the nominal values and the upper and lower extremes are given for over 400 items, including many electronic part categories, over 70 tubes and semiconductors by part number, a variety of electromechanical parts, and some frequently used subassemblies. Application factors K_A serve as multipliers to adapt these failure rates to account for actual conditions of ambient temperature, operating-to-rated wattage, wire size in potentiometers and resistors, and other measures of application severity. The product of the nominal failure rates times the application factors are multiplied, in turn, by an operational factor K_{op} which ranges from 1.0 for a laboratory computer to 2,000 for a booster engine compartment (in flight), to adjust the failure rates for external stresses which may be experienced during actual usage.

Only one significant source of data specifically on mechanical and electromechanical devices has been noted (K1S). This reference provides not only basic data on parts such as motors, synchros, and resolvers, gear boxes, and hydraulic components but also an indication of the methods of estimating the reliability of these devices during actual operation. Informal communications received by the authors indicate that several groups have run tests which tend to validate the material presented in this report.

One author (P4) has suggested that the problem of obtaining specific failure-rate information for the various parts of a module be avoided by defining for each part a "reliability index" which is the ratio of the failure rate of the particular part to the failure rate of a "standard" part that is chosen as the basis for the normalization. This author reasons that it is much easier to obtain an accurate indication of the relative failure rates of parts and that any prediction made using the "reliability indexes" can easily be normalized for a particular situation through the choice of an appropriate value for the failure rate of the "standard" part

Other Prediction Methods

The active element group method (B9, R13, S7) differs from the basic method discussed previously in that the parts population of the module is defined in terms of the number of active elements, i.e., tubes and semiconductors. By definition, an active element group (AEG) consists of a tube or a transistor with a proportionate share of the resistors,

capacitors, coils, transistors, and other parts which form the module. The failure rates for various AEG's may be obtained from published tables (B9, S7) or may be computed from the nominal failure rates of the constituent parts. The failure rate of the module is computed as the sum of the products of the number of AEG's times the appropriate failure rates. This method of analysis provides an easy means for comparing the effects of complexity on reliability. For example, if a designer wishes to add one stage of amplification to a three-stage amplifier, he can readily determine the loss of reliability versus the gain in system performance. Thus the engineer can evaluate easily a number of the factors which he must consider in a trade-off determination.

In situations where the reliability of a large number of modules must be predicted, sampling procedures may be used to advantage. The use of such procedures does not affect the basic technique used in prediction but rather leads to the stipulation that a detailed prediction of reliability will be made for only the selected sample modules whereas merely a quick analysis, if any at all, of the estimated reliability will be made for the other modules. The use of sampling procedures introduces risk factors for both the user and manufacturer of the modules; however, these factors may not be significant in terms of the degree of error that is expected when using usual prediction methods.

Several groups are currently studying the potential value of predicting reliability of standard or preferred circuits packaged in preselected configurations i.e., weldpack, microminiaturized wafers, microelectronic wafers, etc. Unfortunately, the results of these studies are not available at this time.

Effects of Part Variability

In the preceding discussion, it has been assumed that the various parts in a given module can be assigned specific failure rates from appropriate data sources. In actuality, of course, even if the assumption of a constant failure rate is accepted, it is recognized that the reliabilities of the parts employed in a group of similar modules will lie within some specified or assumed range about the nominal values. Furthermore, in establishing a true measure of the inherent reliability of a module, attention must be given not only to the effects of catastrophic failure but also to the effects of degradation resulting from changes and variations in the characteristics of the parts.

Several authors have considered various techniques which may be employed in obtaining a realistic picture of the variations in reliability which may be expected from variations in parts. The methods considered include the use of analysis of variance to obtain the expressions for the module reliability in terms of random variables representing the part characteristics (B6, M10) and the derivation of expressions relating output tolerance to part tolerances (D7, D8, M16) as well as the application of other statistical techniques (M7). An analysis of the effects of part variations can lead to the recognition of areas where improvement is desirable or where changes can be made that will aid in optimizing the reliability of the design.

Prediction of Equipment Reliability

A survey of the current literature reveals a variety of approaches to the prediction of equipment and systems reliability. An analysis of these approaches discloses many points in common and also shows that in some instances several of these approaches must be combined to obtain a valid prediction for a complex equipment. To achieve greatest effectiveness in the use of these techniques, one must define carefully the type of prediction desired and then select the one or more approaches necessary. The ways in which the use of prediction techniques may aid in improvement of equipment, as well as the results of having employed prediction in the development of certain equipments are discussed in Section 6.

Selection of Prediction Technique

The selection of the preferred technique for a particular reliability analysis may be resolved on the basis of the following considerations:

(a) Project Requirements - Does the project require that a specified technique be employed?

(b) Purpose of Prediction - Reliability predictions may be used to establish adequacy of proposed designs at time of bidding, to measure compliance with reliability specifications, and to analyze design improvements. The first two uses require an absolute estimate of the inherent reliability, which is the most difficult type to make with high accuracy. When the purpose of the analysis is to obtain a relative evaluation of alternative designs or to locate major weak links, simplifying assumptions often may be made.

(c) Type of Equipment or System - Several classes of techniques, each relating to particular types of equipment, are available. Some of these techniques are especially useful where a switching-circuit analogy is applicable. Other techniques apply to situations where degradation-type failures must be considered or where the consequence of failure of a part differ according to its mode of failure.

(d) Phase of Design - The phase of the design process determines the amount of detail information available about the equipment and thus which technique may be appropriate.

(e) Reliability versus Other Parameters - In many complex equipments and systems such as those which include alternate modes of operations, the more advanced concept of system effectiveness or system worth (which includes consideration of reliability, maintainability, and related factors) must be employed in obtaining a measure of probability of successful performance

(f) Degree of Accuracy Desired - The refinement of a prediction to include considerations, such as, confidence limits associated with estimates and variations in operational requirements for success during a given mission, naturally leads to the use of more advanced prediction techniques.

Elementary Prediction Techniques

The oldest technique for the numerical prediction of equipment reliability is based on the application of the product rule and simple redundancy considerations. This technique is valid and extremely useful where the modules composing an equipment operate in a simple series and/or redundant configuration with respect to reliability. One of the more mathematical treatments of reliability analysis techniques (A6) discusses the product rule and shows that actually it can be applied with reasonable validity to a variety of situations. A recent publication (C4) provides an excellent description of this technique.

Another approach is the prediction by equipment function. One handbook (S7) prescribes the use of this technique as the first step in a reliability analysis. In this technique, the reliability of a new equipment or system is developed by comparing the function of the new device, or portions thereof, with that of existing devices of similar function and complexity and known reliability. Other activities have recognized the value of this approach and a research study directed at extending the applicability of the technique and provision of backup data is currently contemplated (R12).

A technique useful in the early stages of the design of electronic equipment is based on the active-element-group (AEG) concept which is described in Section 2.3. If simple redundancies are evident in the equipment, the AEG prediction, of course, should be made on a module basis and the module reliabilities combined using the technique considered above.

A fourth technique (B14), sometimes termed "Cause and Effect Analysis", is more qualitative than quantitative. However, when it is applied systematically, it can lead to realistic appraisal of possible sources of unreliability and of the merits of alternative approaches to correct such unreliability. The application of this technique results in a detailed, systematic analysis of the relationship of various parts to the whole; identification of modes of failure and the effects of such failures; analysis of means of eliminating failures; and a summarization of necessary design improvements and expected success of the device in the intended application.

Use of Switching-Circuit Analogy

A number of the earliest papers on the subject of reliability prediction relate to the reliability of switching circuits (B21, F7, G1). Since the switch is a two-state device - either open or closed - it was soon evident that a switching circuit could be considered an analogue of any group of interconnected elements where the operation of each element could be described as either a success or a failure. Thus, the analogy is particularly applicable to equipment such as a missile where the success of the flight depends on the success or failure of the constituent components during the flight interval.

Three steps are essential in the application of the switching-circuit analogy to the prediction of reliability:

(a) Preparation of a circuit diagram where each component is represented by a switch, the open position being analogous to failure and closed position analogous to success.

(b) Derivation of a formula (transfer function) for transmission through the circuit showing all combinations of switch closures which can lead to success.

(c) Interpretation of the formula for successful transmission in terms of probability of success by substituting for symbols denoting switch closure, the probability of such closure; and for symbols denoting open switches, the probability of failure.

In this procedure, the principal effort centers around step (b), the derivation of the formula. Early papers suggest the development of complete tables of all of the independent ways in which success could be obtained and the summation of these terms to achieve the desired formula. Later, symbolic logic (K7, S3) and Boolean algebra were recognized (F7, G1) as valuable aids in the derivation of the required formula.

Extensions of this technique to switches or components which exhibit three distinct states (F7) and to complex milti-element, series-parallel networks (L3) have been described. A more recent paper treats the application to systems which include requirements for sequential operation of its components (K15).

Use of Reliability Block Diagrams

An examination of the usual engineering block diagram for an equipment reveals that the diagram generally depicts the interrelationship between modules or other subportions of the

equipment which must perform successfully if the equipment is to operate successfully. Based on this observation, the idea of preparing a "reliability block diagram" which would show clearly the reliability interrelations, was developed (B12, F9, H13, K10). The principal distinction between a reliability block diagram and the conventional engineering block diagram is that the reliability diagram must include blocks representing power supplies and similar auxiliary devices, the functioning of which contributes directly to the success of the equipment, as well as blocks for those portions of the equipment that perform a primary service in fulfilling the intended function.

The reliatiliby block diagram often may be developed directly from the engineering block diagram through the addition of blocks to represent power supplies and similar units (B12). Another approach (H13) consists of starting with a block labeled "This equipment will perform successfully if" and connecting to that block by appropriate series or series-parallel arrangements blocks describing operations which must be successful if the equipment is to operate successfully. Series blocks are connected with lines bearing the words "and if" and parallel blocks are connected with lines bearing the word "or." Thus it becomes possible to start at the first block and read, "This equipment will perform successfully if... and if... and if... or... etc.," where the resulting sentence provides a complete description of modes of successful operation. The purpose of either of these approaches is to establish a clear means of communicating engineering knowledge concerning the equipment to the mathematician who is to derive the reliability formula. The reliability block diagram often should be accompanied by either a definition of the requirements for equipment success or a tabulation of those minimum combinations of portions of the equipment that will lead to successful equipment operation if they are simultaneously successful.

The next step after obtaining the reliability diagram is to derive the reliability formula describing the probability of successful operation. For equipments where the diagram indicates that the elements are in a simple series-parallel arrangement, the procedures described in Section 3.2 may be employed for the more complex equipments, several procedures based on easy to follow rules that lead to the derivation of valid formulas have been proposed (B12, F9, K10). Boolean algebra may prove useful in this regard, but it is not clear from the literature if this algebra is sufficiently powerful to lead to the derivation of the desired formula without the use of several supplementary rules (B12, H13, K10, R2).

Refinement of Prediction

The techniques discussed so far in this section have related to the problem of deriving a formula, or mathematical model, for the reliability of an equipment under the conditions where a single reliability block diagram or switching-circuit analogue is applicable to the entire period of operation, and the reliability of each portion of the equipment is a constant for that period of operation. Many authors have recognized that such conditions often do not exist; thus, extensions or refinements in the prediction techniques are desirable in order to obtain greater accuracy in the results.

Several papers have discussed the matter of obtaining an estimate of possible variations in equipment reliability due to variations in the reliability of the constituent parts (B6, K10, M10); however, the need for further work is acknowledged (A6). Useful indications of possible variations in equipment reliability may be obtained by making three computations where, respectively, optimistic, expected, and pessimistic values of reliability are assumed for the various parts of the equipment (T5). Another approach is to analyze the variations in equipment reliability with respect to the variations in reliability of the constituent parts through the use of partial derivatives of the reliability formula (B13). Several more advanced techniques are discussed in Section 4.

As the prediction techniques were extended to more complex equipment and systems, it became apparent that some measure of goodness which is more comprehensive than the concept of reliability, as usually employed, would be desirable. One concept (F9, H14, J3) - often called system effectiveness - makes provisions for incorporating considerations such as the relative significance of alternate modes of operation and the effects of maintenance (R12). A recently proposed system-value concept would include not only system effectiveness but also such basic factors as production time, support requirements, and an evaluation of the effectiveness of the equipment in accomplishing the desired function so as to provide an accurate numerical means of choosing between alternative equipments for the same task (K13). The techniques of reliability prediction, perhaps with slight alterations, are basic to both system-effectiveness and system-value calculations. Other techniques necessary in these calculations are beyond the scope of this paper.

Another problem concerns the prediction of reliability for an equipment which during a given period of use may pass through successive intervals where requirements for successful performance vary significantly. In some instances, the desired over-all reliability figure may be obtained from a combination of the reliabilities for the separate nitervals (P2) and in others, the need for techniques of higher mathematics (K16) become apparent.

An excellent means of refining any reliability prediction is to make use of such limited test data as may come available early in the development of the equipment. A recently

reported non-linear estimation technique for obtaining an approximation of the expected value of the constant failure rate of an item of equipment from data obtained during the "debugging" period (R17) is typical of the current effort in this regard.

Advanced Mathematical/Statistical Techniques

Besides the techniques described in the preceding sections, many new ones are being developed in an effort to obtain means for achieving valid predictions of reliability, particularly in complex situations. These new techniques often are derived from the application of advanced mathematical and statistical procedures based on information theory, Monte Carlo methods, linear programing, queuing theory, Boolean algebra, Baye's theorem, and various distribution theories such as exponential, Weibull, gamma, normal, log-normal, chi-square, Poisson, and binomial. In order to apply each of these theories or distributions, appropriate raw failure, usage, replacement, and maintenance-time data, as well as an understanding of the inferences that can be drawn from the ensuing analysis, must be available.

A problem often encountered in reliability studies is that of predicting the probability distribution of some performance parameter. In most cases, an exact analytical solution is not feasible because of the difficulty in the required integration. The distribution of the performance parameter can be obtained, however, by mathematical simulation based on the Monte Carlo method (B16, D10, F2, F4, U1). This method constitutes a "cut and try" approach where the working mechanisms of the equipment are simulated based on the general mathematical model of that equipment.

As an example of this method, consider a simple series circuit configuration expressed by the equation

$$e_d = L\frac{di}{dt} + Ri + \frac{q}{C} + e$$

where e_d is the voltage drop across the LCR circuit as a function of t. It is recognized that the response e_d for a succession of identical pulses of i will not always be the same but rather will have some probability distribution with respect to time. Monte Carlo simulation is one means of defining the distribution of e_d so that realistic safety margins can be established without actual test of the circuit. Appropriate random numbers are used to simulate the distribution of each circuit characteristic, R, L, and C, with respect to time. A cumulative probability distribution then is computed for e_d to obtain the probabilities of exceeding certain limits or safety margins.

Thus, through the use of random numbers and circuit equations, distributions of output performance parameters can be established. Safety margins may be apportioned to the various stages of a design if not to the parts themselves. Since these analyses are only as accurate as the mathematical model used in the simulation, consideration must be given to the possible effect of nonlinearities and interactions that are not included.

In employing Monte Carlo or other simulation techniques, the appropriate distributions for describing the performance parameters must be selected and random numbers with the same underlying distributions generated. (B16, R1). The appropriate distribution, of course, must be selected on the basis of historical knowledge about the expected distribution of a process. A method for programing uniformly distributed random numbers and also random numbers from the exponential, Weibull, log-normal, Poisson, and Chi-square distributions has been developed (J6).

Another tool in today's technology which is finding usefulness in system availability and maintainability studies is queuing theory (B16, B7, K6, M12). Basically this theory is concerned with the optimization of the waiting time (time to repair or replace) subject to random times of arrival (random times to failure). The object is to establish the procedure for servicing the maximum number of arrivals in the shortest possible time.

To illustrate, consider the equipment that experiences random failures over its operating and storage life. Certain periods of time are required to search for and replace various failed parts. The design goal is to establish the equipment configuration that minimizes down time. Queuing theory seeks the best combination of search time and replacement time. If data are available on time to failure, search time, and replacement time, these analyses may be carried out effectively. If appropriate data are unavailable, realistic results often may be obtained by simulating distributions based on the failure rates of the parts or modules.

If the future probability states of an equipment depend only on the immediate past history, then the process is Markovian (B2). Any equipment whose parts fail approximately according to an exponential distribution can be described as a stationary Markov process. A non-stationary Markov process exists where the failure rates change with time. Markovian techniques can be used to consider the effects of both component drift and catastrophic failure (B19, K16).

Among other advanced analysis procedures which might be mentioned are:

(a) The use of vector analysis techniques to study the reliability of multicomponent structures in series and parallel configurations (B10).

(b) The application of Baye's theorem to reliability (B3, M15).

(c) The application of various distributions, their density functions and variances, means, failure rates, etc. (H6).

The advanced mathematical and statistical techniques useful in reliability prediction are generally so complex that it is impossible to present an adequate description of their application, function and value in this survey paper. The reference documents cited can provide the reader with more information on these methods.

Other Prediction Techniques

The literature survey carried out in conjunction with the preparation of this paper reveals that almost all the prediction techniques fall into the categories discussed in Sections 2, 3, and 4. Of the remaining techniques, several deserve mention because of their unique approach and possible application to various situations which the engineer may encounter.

One paper (K5) describes three techniques, the first two of which are reported to be in current use. The first of these, "Predicting Reliability by Using a Standard," leads to the development of "Relative Complexity Factors" which serve as a measure of the relative unreliability of specific parts as compared to the unreliability of some standard, unity-complexity-factor part. The second method, "Predicting Reliability by Using Rating Factors" results in the tabulation of rating factors based on engineering judgment, manufacturing complexity, mean-life data, state-of-the-art, and other information which might affect reliability. It is suggested that several groups of engineers be asked to develop rating factors for the same parts and then a composite set of average values be derived for use in prediction studies. The third method, "Predicting Reliability by Relative Utility Evaluation," is based on the computation of a "K" factor for each device where K is the product of cost times weight times volume. Failure data from a variety of electronic and mechanical subsystems are used to demonstrate that the associated "K" factors are useful predictors of relative reliability.

Another approach to predictions(P5) is to compute the over-all reliability as a product of the design reliability times the component reliability times the reliability of fabrication. Techniques for estimating the latter two expressions in this product are described.

A third paper (R14), which perhaps could have been included in Section 4 of this survey, suggests an approach to system analysis which would organize engineering design information and data on component performance in a way suitable for the application of probability theory and the techniques of mathematical statistics. This approach is shown to be particularly significant when effects such as combined environment, interdependence of failures, and confidence intervals for performance characteristics must be considered.

Use and Validity of Reliability Prediction

Throughout this paper, it has been tacitly assumed that the development of a reliability prediction results in valid information that is distinctly useful in a design program. Several authors (B18, L6, W8, W9) have questioned this assumption; but with the exception of one, they have concluded that when predictions are developed properly, using sufficiently accurate basic information, the results are useful. Others (B8, F1, T6) have pointed to the conditions for making a useful prediction and their resulting value in system analysis. Briefly, predictions have been found to be useful and valid, from a designer's point of view, for obtaining:

(a) An absolute estimate of the inherent reliability of equipment.

(b) Relative evaluations of the reliability of alternative design approaches.

(c) Information on "weak links," as an aid to design improvement.

From a manager's point of view, predictions are useful for:

(1) Establishing adequacy of proposed design at time of bidding.

(2) Measuring conformance to reliability specifications.

(3) Planning reliability test programs; in particular, estimating duration of test programs as an aid in preparation of schedules and budgets.

(4) Analyzing design improvements.

Uses (1), (2), and (3) relate generally to (a), or the obtainment of an absolute estimate of the inherent reliability, whereas (4) relates to items (b) and (c).

One of the basic reasons for developing reliability prediction techniques was to provide means for estimating the reliability of a device from design data in order to obtain a reasonable measure of the adequacy of the design in terms of the specification or use requirements. To achieve a prediction useful for this purpose, great care must be employed in both the development of the mathematical model and the choice of the numerical reliability data for use in the model. The data must be appropriate to the specific parts, the circuit and environmental stresses, and such other factors as may affect the ultimate reliability. Several investigations

have shown that agreement between predicted and measured reliabilities may be within assigned confidence limits. More typical of the results are situations where the measured reliability, in terms of mean-time-between-failure, ranges from one-third to two times the predicted value. A variety of comparisons are discussed in the literature (A7, B20, D2, G1, H2, N1, R6, V2, V3).

Another use of reliability prediction is to obtain comparative evaluations of alternate designs, or of an existing design and a proposed improvement. In situations such as these, if the emphasis is put on the comparison and not on the estimation of the absolute value of the reliability, the requirements for prediction are relaxed and greater accuracy may be expected. To obtain this accuracy, the same basic rules must be followed in the analysis of the alternate designs; and comparable reliability data must be used. Of course, many variations in design may be studied; the literature gives particular attention to the use of prediction techniques in the analysis of the effects of redundancy (B1, K12, M9).

Perhaps the most valuable use of reliability prediction is in the analysis of a design to establish its weakest links from the point of view of reliability, as an aid in design improvement. The simplest approach in this regard is merely to make gross comparisons between the reliability of various modules in the equipment to establish those modules which exhibit the lowest reliability. As the complexity of a system grows, a simple inspection of the results of the prediction may not be adequate. Under these circumstances, a useful procedure is to evaluate the partial derivatives of the reliability formula for the equipment with respect to the reliability of its constituent parts to establish which module reliabilities can cause the greatest change in equipment reliability (B13, L3). More advanced mathematical techniques, some of which are described briefly in Section 4, also are useful in this regard either singly or in conjunction with computer studies.

Concluding Remarks

As noted in the introduction, the purpose of this paper is to provide a compendium of information useful to an engineer in selecting the reliability prediction technique appropriate to his requirements. In fulfilling this purpose we have evolved a guide to those basic techniques which have received reasonably wide acceptance and have listed a considerable number of references which have received reasonably wide acceptance and have listed a considerable number of references which may be consulted for further information.

As is well recognized, reliability engineering technology is dynamic, constantly growing and expanding, so that even as these words are written, new techniques for prediction are being hypothesized and older techniques are being substantiated and/or improved. Therefore, we offer this work as a stepping stone from the old to the new with the hope that it will aid many groups in obtaining maximum benefit from the current technology as the need for reliability prediction increases for both military and commercial products.

The authors will welcome correspondence from any who wish to aid in maintaining this compendium complete and up to date. To facilitate the utilization of correspondence, it is requested that a copy of any communication, including enclosures thereto, be sent to each author.

Acknowledgment

The authors gratefully acknowledge the assistance rendered by many who responded to informal requests for information on publications related to reliability prediction. In particular, they appreciate helpful letters and comments received from Messrs. I. Doshay, G. R. Grainger, H. J. Kennedy, C. A. Krohn, R. E. Moe, E. J. Nucci, L. J. Paddison, and E. Shecter. Further, they wish to thank the authors of earlier papers on this subject who, through the inclusion of bibliographies in their papers, provided guides to earlier articles on this subject. If articles of significance have not been referenced, their authors are asked not to take offense but rather to provide information that will facilitate the correction of the omission.

Bibliography

1. Armed Services Technical Information Agency, "Bibliography on Reliability, " (On file cards.)
2. Institute of Technology, Air Univ. USAF, "Reliability, A Subject Bibliography, " by Tibor Vineze, Tech. Report No. 61-1, Feb. 23, 1961.
3. Office of Technical Services, "Reliability and Quality Control - Selective Bibliography, " Dept. of Commerce, Report No. SB 405, 1950 - 1960.
4. Rand Corp., "Rand Publications on Reliability," Report No. RM2613, July 15, 1960, compiled by D. S. Stoller.
5. U. S. Navy Electronics Laboratory, "NEL Reliability Bibliography", May 1956 with supplements, OTS PB121838 and PB121838S.
6. "Literature Guide on Failure Control and Reliability", Capt. W. F. Luebbert, Signal Corps Tech. Report 13, December 31, 1956, Stanford Electronics Lab., Stanford Univ. (contract NOnr 225(24), NR373-360).

A1 Abhyander, S., "Investigation of Mathematical Methods for the Analysis and Synthesis of Computer Circuits", Sept. 1956, ASTIA AD110120.

A2 Acheson, M.A., "Electron Tube Life and Reliability", Sylvania Electric Products Inc. 1956, Chapt. V.

A3 Aeronautical Radio, Inc., "Investigation of Electronic Equipment Reliability", Air Force Reliability Assurance Program, Progress Report No. 1, Feb. 15, 1956.

A4 AGREE, "Reliability of Military Electronic Equipment", Office of Asst. Sec. of Defense, June 4, 1957.

A5 Albrecht, N. and Pascucci, D., "Technique for the Physical Survivability Analysis of a Communication Network", Proc. 5th Nat'l Symp. on Global Communications.

A6 Allen, W.R., Tick, L.J., Woodbury, M.A., "Some Mathematical and Statistical Techniques Useful in Reliability Analysis", Proc. 4th Nat'l Symp. Rel. and Q.C., Jan. 6-8, 1958, pp. 63-68.

A7 ARinc Research Corporation, "Yearly Review of Progress", July 15, 1960, Pub. No. 101-28-166.

A8 Army Ordnance Missile Command, "AOMC-Contractor Reliability Conference", Redstone Arsenal, Dec. 16, 1958.

B1 Balaban, H.S., "Some Effects of Redundancy on System Reliability", Proc. 6th Nat'l Symp. Rel and Q.C., Jan 11-13, 1960, pp. 388-402.

B2 Barlow, R.E. and Hunter, L.C., "Mathematical Models for System Reliability", Sylvania Electronic Defense Labs, Report No. EDL-E 35., Aug. 11, 1959.

B3 Bazovsky, I., "Reliability: Theory and Practice", Prentice Hall, 1961.

B4 Bear, J.C., "Elements of Reliability Prediction", ARINC Research Corp., Publ. No. 98, Oct. 1, 1956.

B5 Bellman, R and Dreyfus, S., "Dynamic Programming and the Reliability of Multicomponent Devices", The Rand Corporation, Report No. P-1139, Sept. 10, 1959.

B6 Benner, A.H. and Meredith, B., "Designing Reliability into Electronic Circuits", Proc. Nat'l Electronics Conference, Vol. 10, 1954 pp. 137-145 (also RCA Report EM-4208).

B7 Bharucha-Reid, A.T., "Elements of the Theory of Markov Processes and Their Applications", McGraw-Hill Book Co., Inc. 1960.

B8 Bird, G.T., "On the Basic Concepts of Reliability Prediction", Proc. 7th Nat'l Symp. Rel and Q.C., Jan 9-11, 1961, pp. 51-55.

B9 Bird, G.T., "On Reliability Prediction in Satellite Systems", ARINC Research Corp. Pub. No. 4226-1-205, May 1960.

B10 Birnbaum, Z.W., Esary, J.D., and Saunders, S.C., "Multi-Component Systems and Structures and Their Reliability", Technometrics, Vol 3, No. 1, Feb. 1961.

B11 Black, G. "A Critical Survey of Electronic Component Failure Rates", Sylvania Electric Products Inc., Mtn. View, Calif., Tech. Memo EDl-M175, Jan 31, 1959 (contract DA 36-039 SC78281).

B12 Blanton, E., "Reliability Prediction Technique for Use in Design of Complex Systems" Hycon Eastern, Inc., Report No. AV7M, Jan 21, 1957. Also paper by same title, IRE Nat'l Convention Record, Vol 5, Part 10, 1957. Condensation of paper published as "Reliability-Design Technique for Complex Systems," Electronic Design, Vol. 5, No. 17, Sept. 1, 1957.

B13 Blanton, H.E., "Reliability-Sensitivity-Function Analysis", Electronic Design, Vol. 6, No. 4, Feb. 19, 1958.

B14 Boeing Company Aerospace Division, "Reliability Manual", (revised to 8-1-61) Document No. D2-3246.

B15 Bosinoff, I. and Klion, J., "Development of New Prediction Techniques", Proc. 8th Nat'l Symp. Rel and Q.C., Jan 9-11, 1962.

B16 Bosinoff, I., Jacobs, R., Fradette, D., "Mathematical Simulation Study", Technical Report, Sylvania Electronic Systems, Waltham, Mass., Oct. 1, 1961.

B17 Bosinoff, I. "Design Goal for Reliability", Proc. 7th Nat'l Symp. Rel and Q.C., Jan. 9-11, 1961, pp. 340-343.

B18 Boyes, W.E., "The Practicality of Predicting Reliability Numbers", Proc. 6th Nat'l Symp. Rel and Q.C., Jan 11-13, 1960, pp. 282-285.

B19 Brender, D.M. and Tainiter, M., "A Markovian Model for Predicting the Reliability of an Electronic Circuit from Data on Component Drift and Failure", IRE International Convention Record, Vol. 9, Part 6, 1961, pp. 230-241.

B20 Brown, H.B., Fredrick, W.C., Kennedy, H.J., "Improved Techniques for Design-Stage Prediction", Air Force Reliability Assurance Program, Progress Report No. 2, Vol. 1, Arinc Research Corp., Pub. No. 110-1-136, April 1, 1959.

B21 Buehler, R.J., "A Study of the Accuracy and Reliability of Compound Circuits", Sandia Corp., Report No. SC-2324(TR) I., May 13, 1952.

C1 Cahn, A.S., "Reliability, Quality Control and Simulation", The Rand Corp. Report No. P-1623, March 2, 1959.

C2 Carhart, R.R., "Reliability in Guided Missile Systems", The Rand Corp. Report No. P-315, July 7, 1952.

C3 Carhart, R.R., "A Current Status of Electronic Reliability Problem", The Rand Corp. report No. RM-1131, Aug 14, 1953.

C4 Christian, J and Hollander, K.W., "Reliability of Switching Mechanisms", ARINC Research Corp. Pub. No. 125-1-203, Jan. 1961. (Also published as Rome Air Development Center RADC-TR-60-239.)

C5 Christopher, G. F., Karmiol, E. D., Youtcheff, J. S., "Prediction of Missile System Survival in a Vibration Environment", Environmental Quarterly, Vol. 5, No. 1, Jan 1959.

C6 Chukreev, Malikov, Polovko, Romanov, "Fundamentals of the Theory and Computation of Reliability", Sudpromgiz, 1959, (Book in Russian).

C7 Connor, J. A., "A Systematic Plan for Predicting Electronic Equipment Reliability", Proc. 1956 Electronic Component Conf., 1956.

C8 Connor, J. A., "Prediction of Reliability", Proc. 6th Nat'l Symp. Rel. and Q. C., Jan. 11-13, 1960, pp. 134-154.

C9 Crawford, J. R., "Estimating Reliability", Transactions Middle Atlantic Region and Aircraft and Missiles Div. 9th Annual Conf. ASQC 1959.

C10 Creveling, C. J., "Increasing the Reliability of Electronic Equipment by the Use of Redundant Circuits", Naval Research Lab., Report 4631, Dec. 5, 1955.

D1 Davis, D. J., "An Analysis of Some Failure Data", The Rand Corp., Report No. P-183 Feb. 12, 1952.

D2 Davis, R. A., Wahrhaftig, W., "Reliability Predictions, A Case History", IRE Transactions on Rel and Q. C., Vol RQC-9, No. 1 April 1960, pp. 87-90.

D3 Davis, R. G., "Some Relations Between Systen and Component Reliabilities", Proc. of Joint Military-Industry Guided Missile Rel. Symp., Redstone Arsenal, Report No. OY3, Vol. 2, Oct. 15-17, 1956, pp. 18-1, - 18-9.

D5 Doshay, I., "Reliability Analysis of Ablester Stage", Aerojet General Corp., Report No. LO358-01-10, Sec III, Sept. 15, 1960.

D6 Doshay, I., "Reliability Monitoring Report for Ablester Stage", Aerojet General Corp. Report No. 2042, June 1961.

D7 Dreste, F. E., "Circuit Design Concepts for High Reliability", Proc. 6th Nat'l Symp. Rel. and Q. C., Jan. 11-13, 1960, pp. 121-133.

D8 Dreste, F. E., "Statistics: Key to Reliable Military Electronic Design", Military Electronics, Vol. VI, No. 3, Mar. 1959, pp. 4, 6, 8.

D9 Dreyfus, S. (See B5).

D10 Driggs, D. H., "Monte Carlo Method of Operational Research", May 1955, ASTIA AD138061.

D11 Durand, T. S. and Johnston, D. E., "A Compilation of Component Field Reliability Data Useful in Systems Preliminary Design" WADD TR60-330, ASTIA AD322822.

E1 Earles, D. R., "Dynamic Reliability Apportionment", Martin-Denver, Report No. M60-43, Nov. 1960.

E2 Earles, D. R., "Component Part Failure Rates Associated with Installation Environment", Martin-Denver, Report No. M60-47, Dec. 1960.

E3 Earles, D. R., "Reliability Growth Prediction During the Initial Design Analysis", Proceedings 7th Nat'l Symp. Rel. and Q. C., Jan. 9-11, pp. 380-393.

E4 Earles, D. R., "Reliability Application and Analysis Guide", Martin-Denver, Report No. M1-60-54 (Rev. 1), July 1961 (Failure Rate Handbook).

E5 Esary, J. D. (See B10).

E6 Estes, C., "Study of Electronic Equipment Life Prediction", Third Quarterly Progress Report, Motorola Inc., April 30, 1960, ASTIA AD243581.

E7 Estes, C., "Study of Electronic Equipment Life Prediction", Fourth Quarterly Progress Report, Motorola Inc., July 31, 1960, ASTIA AD244208.

E8 Estes, S. E., "Methods of Determining Effects of Component Redundancy on Reliability", MIT, Aug 1958, ASTIA AD205965.

F1 Farrier, J. M., "Designing in the Dark", Proc. 6th Nat'l Symp. Rel. and Q. C., Jan. 11-13, 1960, pp. 431-437.

F2 Feinauer, E., "Monte Carlo Evaluation of Single Scattering Integrals", March 1961, ASTIA AD47251.

F3 Firstman, S. I., "The Application of Random Sampling Simulation to Reliability Estimating", Proc. 3rd Exploratory Conf. on Missile Model Design for Rel. Prediction, White Sands, N. M., April 20-23, 1959. (See also the Rand Corp. Report no. P-1638, March 16, 1959.)

F4 Firstman, S. I., "Monte Carlo Models for Estimating Reliability: An Exploratory Analysis", The Rand Corp., Report No. RM 2149, June 5, 1958, ASTIA AD213036.

F5 Firstman, S. I., "Reliability Estimating by the use of Random Sampling Simulation", The Rand Corp., Report No. P-1521, Oct. 20, 1958.

F6 Fradette, D. (see B16)

F7 Frantik, R. O., "The Determination, Application and Limitations of Circuit Reliability Equations", Sandia Corp. Report No. SC-3288(TR), April 26, 1954.

F8 Fredrick, W. C. (See B20)

F9 Friddell, H. G., and Jacks, H. G., "System Operational Effectiveness (Reliability, Performance, Maintainability)", Proc. 5th Nat'l Symp. on Rel. and Q. C., Jan 12-14, 1959, pp. 179-196. Also published in Research and Development Reliability, Electronics Division, ASQC, Feb. 1961, pp. 76-118.

G1 Gates, C.R. "The Reliability of Redundant Systems", JPL~California Institute of Technology, Memo 20-76, Aug. 27, 1952.

G2 Gray, H. J., "An Application of Piecewise Approximations to Reliability and Statistical Design", Proc. of IRE, Vol. 47, No. 7, July 1959.

H1 Harris, T. E., "A Model for the Reliability of Complex Mechanisms", The Rand Corp. Report No. RM302, Dec. 5, 1949.
H2 Harris V. and Tall, M. M., "Progress Report on Reliability Prediction", Proc. 2nd Nat'l Symp. on Rel.and Q. C., Jan 9-11, 1956 pp. 99-121.
H3 Harshbarger, B., Editor, Proceedings of the Statistical Techniques in Missile Evaluation Symposium, Director of Guided Missiles, Office of Secretary of Defense and Office of Ordnance Research, 1958.
H4 Hedetniemi, C. J. and Herd, G. R., "Predicting the Reliability of Airborne Equipment" Electronic Industries and Tele-Tech., Sept. 1956.
H5 Herd, G. R. (See H4)
H6 Herd, G. R., "Some Statistical Concepts and Techniques for Reliability Analysis and Prediction", Proc. 5th Natl Symp. Rel. and Q. C. Jan. 12-14, 1959, pp. 126-136.
H7 Herd, G. R., "Estimation of Equipment Reliability", ARINC Research Corp., Pub. No. 68, May 26, 1955.
H8 Herd, G. R., "Estimation of Reliability Functions", ARINC Research Corp., Pub. No. 87, May 1, 1956.
H9 Herd, G. R., "Application of Statistical Methods in Evaluating Performance of Electronic Equipment", Annual Convention Transactions, ASQC, 1953.
H10 Hershey, J. H., "Reliability and Maintainability of Military Electronic Equipment", presented at 3rd Signal Maintenance Symp., Ft. Monmouth, N. J., April 14-16, 1959, (Data included in this paper from handbook Military Reliability Information, Bell Telephone Laboratories.)
H11 Hinrichs, R. H., "A Second Statistical Method for Analyzing the Performance Variation of Electronic Circuits", Convair, San Diego, Report ZX-7-010, Feb. 15, 1956.
H12 Hollander, K. W. (See C4)
H13 Holtzman, C. W. Jr. and Marshall, W. E., "A New Method of Communication Between Engineer and Mathematician Aids System Reliability Prediction", Proc. 6th Natl. Symp. Rel. and Q. C., Jan. 11-13, 1960, pp. 403-408.
H14 Horne, R. C. Jr. and Welker, E. L., "Concepts Associated with System Effectiveness", ARINC Research Corp., Pub. No. 123-4-163 July 15, 1960.
H15 Hosford, J. E., "Measures of Dependability" Philco Western Development Lab., Palo Alto, May 1959.
H16 Howard, W. J., "Chain Reliability: A Simple Failure Model for Complex Mechanisms", The Rand Corp., Report No. RM-1058, March 27, 1953.
H17 Howard, W. J., "Some Physical Qualifications for Reliability Formulas", The Rand Corp. Report No. RM-724, June 1, 1956.
H18 Hunter, S. (See B2).

J1 Jacks, H. G. (See F9)
J2 Jacobs, R. (See B16)
J3 Jaffe, H. and Rosenthal, S. A., and Katz, M. "A Measure of Reliability and Information Quality in Redundant Systems", IRE Transactions on Rel and Q. C., Vol. RQC-10, No. 1, March 1961, pp. 29-37.
J4 Johnston, D. E. (See D11)
J5 Johnston and Macruer, "A Summary of Component Failure Rate and Weighting Function Data and Their Use in Systems Preliminary Design", WADC TR57-668, Dec. 1957, ASTIA AD142120.
J6 Juncosa, "Random Number Generation on the BRL High Speed Computing Machine", Ballistic Research Lab., Report No. 855, May 3, 1953.
J7 Jaffe, H. and Katz, M. D., and Rosenthal, S. A., "Designing Reliability into the B-58 Bombing-Navigation System", Proc. 7th Natl Symp. Rel and Q. C., Jan 9-11, 1961, pp. 273-282.

K1 Kennedy, H. J. (See B20)
K2 Karmiol, E. D. (See C5)
K3 Katz, M. D. (See J3)
K4 Katz, M. D. (See J7)
K5 Kaufmann, M. I. and Kaufman, R. A., "Predicting Reliability", Machine Design, Aug. 18, 1960, pp. 178-184.
K6 Keilson, J. and Kooharian, A., "On Time Dependent Queuing Processes", Annals Mathematical Statistics, Vol. 31, 1960.
K7 Keister, Ritchie, and Washburn, "The Design of Switching Circuits", D. Van Nostrand Co., New York, 1952.
K8 Kirby, M. J., and Powell, H. R., "Prediction of Missile Reliability", Sperry Engineering Review, July-Aug. 1955.
K9 Kirkpatrick, I., "Predicting Reliability of Electro-Mechanical Devices", Proc. 6th Natl Symp. Rel. and Q. C., Jan 11-13, 1960 pp. 272-281.
K10 Kleinerman, M. M. and Weiss, G. H., "On The Reliability of Networks", Proc. of Natl Electronics Conf., Vol. 10, 1954, pp. 128-136.
K11 Klion, J. (See B15)
K12 Kneale, S. G., "Reliability of Parallel Systems with Repair and Switching", Proc. 7th Natl Symp. Rel and Q. C., Jan. 9-11, 1961 pp. 129-133.
K13 Knight, C. R., "General Factors in System Effectiveness", Presented at EIA M5 Comm. on Military Electronics Systems, Wash. D. C. Sept. 26, 1961.
K14 Kochendorfer, D. C., "Application of Theoretical Concepts in Reliability Studies", ARINC Research Corp., Pub. No. 72, Sep. 20, 1955.
K15 Kirkpatrick, I., "Proposed Procedures for Reliability Stress Analysis of Mechanical and Electro-Mechanical Devices", Report No. 176, Feb. 27, 1958, RCA Victor Co., Ltd.
K16 Kleinerman, M. M. and Weiss, G. H., "The Reliability of Sequentially Operated Networks" IRE International Conv. Record, Vol. 9, Part 6, 1961, pp. 222-229.

L1 Lacey, H. E., "A Natural Approach to the Calculation of Systems Reliability", U. S. Naval Ordnance Labs., White Oaks, Maryland, Oct. 31, 1957, ASTIA AD150783.

L2 Landers, R. R., "Method for Measuring, Analyzing and Predicting Reliability and Performance of Large, Complex Electronic Equipment", First Technical Guided Missile Symp., Los Angeles, June 21, 1956.

L3 Lipp, J. P., "Topology of Switching Elements vs. Reliability", IRE Trans. on Rel & Q. C., No. PGRQC-10, June 1957, pp. 21-33.

L4 Locurto, C. A., "Reliability Design Analysis Manual", General Electric Missile and Space Vehicle Dept., Report No. R60SD552, Mar. 11, 1960.

L5 Luebbert, W. F., "Achieving Operational Effectiveness and Reliability with Unreliable Components and Equipment", IRE Convention Record, Vol. 4, Part 6, 1956, pp. 41-50.

L6 Lusser, R., "Predicting Reliability", Redstone Arsenal, October 1957.

L7 Lusser, R., "A Study of Methods for Achieving Reliability of Guided Missiles", Redstone Arsenal, reproduced from NAMTC Technical Report No. 75, US NAMTC Pt. Mugu, July 10, 1950.

M1 Madansky, A., "Use of Tolerance Limits in Missile Reliability Analysis", The Rand Corp Report No. RM-2423, Jan 13, 1960.

M2 Madansky, A., "Approximate Confidence Limits for the Reliability of Series and Parallel Systems", The Rand Corp., Report No. RM-2552, April 4, 1960.

M3 Madison, R. L., "An Analysis of the Effects of Maintenance on Part Replacements", Proc. 4th Natl Symp. Rel & Q. C., Jan 6-8, 1958, pp. 19-29.

M4 Malikov (See C6)

M5 Marini, J., Williams, R., "Evaluation & Prediction of Circuit Performance by Statistical Techniques", IRE Trans. on Rel. & Q. C., Vol. RQC-9, No. 1, April 1960, pp. 40-52.

M6 Marini, J., Brown, H., and Williams, R., "The Evaluation and Prediction of Circuit Performance by Statistical Techniques," ARINC Research Corp., Pub. No. 113, Feb. 14, 1958.

M7 Marini, J. and Williams R. T., "The Evaluation and Prediction of Circuit Performance by Statistical Techniques", Proc. Joint Military-Industry Guided Missiles Rel. Symp. Pt. Mugu, Nov. 5, 1957.

M8 Marshall, W. E. (See H13).

M9 McLean, J. B. and Moskowitz, F., "Some Reliability Aspects of Systems Design", IRE Convention Record, Vol. 4 Part 6, Mar. 1956 pp. 50-59. Also paper by same title, IRE Trans. on Rel. & Q. C. No. PGRQC-8, Sept. 1956, pp. 7-35.

M10 Meltzer, S. A., "Designing for Reliability", IRE Trans. on Rel. & Q. C., No. PGRQC-8, Sept. 1956, pp. 36-43.

M11 Meredith, B. (See B6)

M12 Morse, P. M., "Queues, Inventories and Maintenance", John Wiley & Sons, 1958.

M13 Moskowitz, F. (See M9)

M14 Moskowitz, F., "Statistical Analysis of Redundant Systems", Lab for Electronics, Boston, Mass. March 29, 1960.

M15 Mosteller, F., Rourke, R. E., & Thomas, G. B. Jr., "Probability with Statistical Applications", Addison-Wesley Pub. Co., Inc. 1961.

M16 Motorola, Inc., Western Military Electronics Center, "Reliability and Components Handbook", Revised 1-30-59.

N1 Naresky, J. J., "Reliability Prediction and Test Results on USAF Ground Electronic Equipment", RADC-TN-58-177, July 1958, ASTIA AD148794. Also IRE Natl Conv. Record, Vol. 6, Part 6, 1958, pp. 165-177.

N2 Nozick, S., "Reliability Estimation, Prediction and Measurement", Electromechanical Design, Jan/Feb. 1958.

O1 O'Leary, W. J., "Product Design Assurance Basic Reliability Concepts", RCA, Camden N. J., Report No. EM-60-418-75, Nov. 15, 1960.

O2 Ordnance Corps, Dept. of the Army (Reliability Branch, Diamond ordnance Fuze Labs) "Reliability Engineering Notes", April 1960.

P1 Pascucci, D. (See A5)

P2 Philipson, J. L., "Operational Reliability Model for a Reconnaissance System", IRE Natl Conv. Record, Vol. 7, Part 6, March 1959, pp. 79-88.

P3 Polovko (See M4)

P4 Polovko, A. M. "On Computing the Reliability of Complex Automatic Systems", Izvestia Akad. Nauk, Otdel. Tekh. Nauk, Energetika i Automatika No. 5, 174-78, Sept/Oct. 1960 (English translation published in Automation Express, Vol. 3 No. 6, Feb. 1961, pp. 37).

P5 Portz, K. E., Smith, H. R., "Method for the Determination of Reliability", IRE Trans. on Rel. & Q. C., No. PGRQC-11, Aug. 1957 pp. 65-73.

P6 Powell, H. R. (See K8)

P7 Price, H. W., "Reliability of Parallel Electronic Components", Proc. 1st Symp. on Military Elec. Rel. and Maintainability also Proc. 5th Joint Military-Industry Symp on Guided Missile Reliability.

R1 Rand Corp. "A Million Random Digits", Free Press c1955.

R2 Randazzo, F. P., Stahl, W. J., "Generalized Mathematical Model for Reliability Studies of Electronic Equipment Complexes", IRE International Conv. Record, Vol. 9, Part 6 1961, pp. 216-221.

R3 RCA, "Reliability Stress Analysis for Electronic Equipment", Report No. TR-1100, Nov. 28, 1956. (Also issued as NAVships 900-193 and OTS, Dept. of Comm., PB 131678). Subsequent revision included in section 8, RADC Reliability Notebook,

R3 (cont) RADC TR-58-111, Sept. 1, 1960, ASTIA AD148868, OTS PB 161894-1.

R4 RCA Service Co., "Philosophy and Guidelines for Reliability Prediction of Ground Electronic Equipments", Report No. R4-57, Oct. 15, 1957, ASTIA AD148556.

R5 RCA Service Co., "A Prediction of AN/GPX-20 Reliability", Report No. R-3-57, ASTIA AD 148562.

R6 RCA Service Co., "Prediction & Measurement of Air Force Ground Electronic Equipment Reliability", Report No. RADC TN58-307, Aug. 15, 1958.

R7 RCA Victor Co. (See K15)

R8 Reeves, T. C., "Reliability--Predicting Thermal Results", Military Electronics, July 1957.

R9 Ritchie (See K7)

R10 Romanov (See M4)

R11 RADC Reliability Notebook, Report No. RADC-TR-58-111, rev. to ASTIA AD148868, OTS PB161894 and PB161894-1.

R12 RADC, "System Reliability Prediction by Function", PR No. 152097, Oct. 16, 1961 and "System Effectiveness Prediction Model PR152098, Oct. 16, 1961.

R13 RADC, "A Technique for Estimating Ballpark Reliability Figures by Tube Counting", Report No. RADC TN-58-81, Mar. 1958. ASTIA 148647.

R14 Rosenblatt, J. R., "On Prediction of System Performance from Information on Component Performance", Proc. of the Western Joint Computer Conf. Feb 1957, pp. 85-94.

R15 Rosenthal, S. A. (See J3)

R16 Rosenthal, S. A. (See K3)

R17 Rosner, N., "Systems Analysis-Non-Linear Estimation Techniques", Proc. 7th Natl Symp. Rel. & Q. C., Jan 9-11, 1961, pp. 203.

R18 Ross, H. D., "Development of Advanced Circuits and Circuit Reliability Techniques" International Business Machine Co., March 31, 1959, ASTIA AD217664.

S1 Saunders, S. C. (See B10)

S2 Scott, S.R. "Consideration of Deterioration Effects in Equipment Reliability Improvement Programs", ARINC Research Corp. Pub. No. 119, May 14, 1958. Also Proc. Natl Conf. on Aero. Elec. May 1958.

S3 Shannon, Claude, E., "A Symbolic Analysis of Relay and Switching Circuits", Trans. of the AIEE, Vol 57, 1938.

S4 Smith, H. R. (See P5)

S5 Stahl, W. J. (See R2)

S6 Sternberg, A., "Reliability Trade-Off Analysis Manual", General Electric, Missile & Space Vehicle Dept. Jan 1960.

S7 Stokes, R. G., "Handbook for the Prediction of Shipboard and Shore Electronic Equipment Reliability", Vitro Labs., Report No. 133, April 1961. (Also NAVships 93820.)

S8 Stokes, R. G., "Results of a Test of Reliability Prediction Technique and Development of a Correlation Factor for Field vs. Laboratory Reliability Measurements," Proc. 5th Natl Symp. Rel & Q. C., Jan 12-14, 1959 pp. 333-342.

S9 Stoller, D. S., "A Failure Model for Equipment Undergoing Complex Operation", The Rand Corp. Report No. P-927.

T1 Tainiter, M. (See B19)

T2 Tall, M. M. (See H2)

T3 Taylor, N. H., "Designing for Reliability" MIT/Lincoln Lab., Report No. TR 102, Dec. 9, 1955.

T4 Tick, L. J. (See A6)

T5 Tiger, B., "Prediction of MTBF Bounds in Early Design", Proc. 6th Natl Symp. Rel. & Q. C., Jan 11-13, 1960, pp. 286-292.

T6 Troxel, D. I. & Wuerffel, H. L., "Design Reliability Analysis--A Proven Technique for Product Control and Enhancement", Proc. 6th Natl Symp. Rel & Q. C., Jan 11-13, 1960, pp. 377-387.

T7 Tsao, T. C. & Walth, C. - Editors, "Electron Tube Life Factors", Engineering Publishers, 1959.

U1 U. S. Government Printing Office, "Monte Carlo Method", Proc. of a Symp. sponsored by The Rand Corp. and Natl Bureau of Stds. Los Angeles, June 29 and 30, 1949.

V1 Vitro Laboratories, "A Summary of Reliability Prediction and Measurement Guidelines for Shipboard Electronic Equipment", Report No. 98, April 15, 1957. (See S7 also)

V2 Vitro Laboratories, "Techniques for Reliability Measurement and Prediction Based on Field Failure Data", Report No. 80, Oct. 10, 1955. (See S7 also)

V3 Voegtlen, H. D., "The RADC Reliability Prediction and Measurement Study", Military Elec. Rel. & Maintainability Symp., RADC TR-58-139B, Vol. 2, Nov. 1958, ASTIA AD148952.

W1 Wahrhaftig, W. (See D2)

W2 Walsh, C. (See T7)

W3 Washburn (See K7)

W4 Weiss, G. H. (See K10)

W5 Weiss, G. H. (See K16)

W6 Welker, E. L. (See H14)

W7 Whitesitt, J., "Boolean Algebra and Its Applications", Addison-Wesley Pub. Co. 1961

W8 Williams, R. T., "The Value of Design Prediction", Proc. 7th Natl Symp. Rel & Q. C. Jan 9-11, 1961, pp. 375-379.

W9 Williams, R. T., "Reliability Prediction Procedures , Implementing Reliability Control", 5th Navy-Industry Conf. on Material Reliability, Nov. 1, 2, 1961.

W10 Williams, R. T. (See M5 and M7)

W11 Woodbury, M. A. (See A6)

W12 Wuerffel, H. L. (See T6)

W13 Wuerffel, H. L., "Reliability Theory and Vital Engineering Interpretations", Proc. of the 1956 Elec. Comp. Conf. 1956.

W14 Wuerffel, H. L., "Reliability Prediction", Supplement of Newsletter, Electronics Div. ASQC, April 1, 1960.

Y1 Youtcheff, J. S., (See C5)

HYDRAULIC CONTROL RELIABILITY IN SPACE VEHICLES

By
A. B. Billet
Senior Staff Engineer
Vickers Incorporated
Detroit, Michigan

Summary

17297

This paper is concerned with the reliability of hydraulic controls on present missiles and space vehicles. The special techniques and problems that required solving are reviewed to meet the high reliability requirements of the control systems of the Minuteman, Atlas, Polaris, and Skybolt vehicles.

This has resulted in the development of new reliability techniques and analyses to meet these requirements.

Introduction

It is highly significant that as we enter our fifth year of space exploration we see continual added emphasis being placed upon the reliability of space vehicles.

With the entry of man into the space environment the need for reliability has become even greater. We are not only concerned with the many million dollars of money expenditures, but now we are concerned with reliability in regard to human life. During the latter part of this decade we will see the beginning of lunar exploration.

It speaks well for reliability that the United States' first space effort, Explorer I, a 31 lb. cylinder, which was launched on January 31, 1958, is still in orbit. It is truly significant reliability-wise that this pioneer spacecraft may still be in orbit when man first sets foot on the moon during the latter part of this decade.

I believe that 1962 will prove to be one of the most phenomenal and active years in the Golden Decade, 1960 to 1970, of space exploration. The year 1962 will probably see a total of 5 to 6 manned orbital space flights with two of these probably being of the 18 orbital type. This same year will probably see more than 10 major launch vehicle tests including those of the Scout, Centaur, and Saturn vehicles.

Other space efforts will probably include six communication vehicles, five meteorological, and perhaps the most significant of all, the beginning of our lunar exploration work on the Ranger program.

It is highly significant to these vital space programs that the Aerospace Industry now recognizes that reliability is one of the most pertinent parts of these programs.

Hydraulic Controls in Space Environments

In respect to the new problems and new environment studies that space travel has brought about, special consideration has been given to further the development and further increase the reliability of hydraulic controls for these space vehicles.

Figure 1 shows a summary of the major environmental conditions that might be expected in the next ten years of space flight. The preliminary instrumentation satellites have shown that in some cases some of the actual environments encountered were considerably different than that previously thought to exist. I believe that much of our future exploration of space will be based upon the fact that in a past three year period the United States has launched 66 instrumentation satellites.

The hyper-environments that the control equipment must be designed to either operate in, or be in satisfactory static condition in, include the natural environments such as high temperature and temperature shock, low ambient pressure, ozone content, radiation, cosmic rays, disassociation (atomic oxygen), and others.

Figure 2 shows possible projected space vehicles during the next seven years, together with those of the past five years.

Minimizing Space Environments

One of the major ways of reducing the effects of these combined environments is the integrated packaging of these hydraulic controls for space operation. Typical of this packaging of equipment is shown in Figure 3, showing the cutaway of a motor-pump used in the Minuteman Missile application.

The packaging of components minimizes or eliminates such problems as external leakage, varying effects of gravity in widely spaced components, and other problems. The Figure 3 packaging contains an electric motor, hydraulic pump, reservoir, hydraulic filter, check valve, pressure transducer, pressure switch, fill and bleed disconnects.

For minimizing temperature effects in many hydraulic system components used in outer space, stainless steel "O" rings are used in place of seals made from elastomeric material. In the case of the electric drive motor, a thermistor is imbedded in the motor field coil to measure critical operating temperatures of the motor and prevent inadvertent overheating during operation. The thermistor can be used in an electrical bridge circuit to automatically cut or reduce power in the event that overheating occurs.

For minimization of the effects of low ambient pressures and weightlessness, the integrated hydraulic system package is the most effective means in reducing these effects. As in the case of the motorpump shown in Figure 3, a sealed steel bellows "bootstrap" type reservoir is used for pressurizing the inlet side of the system. The "bootstrap" type reservoir uses high system pressure on a differential area to pressurize the low pressure part of the system.

Space Reliability Of Hydraulic Controls

As a result of the combined environmental operating conditions and the resultant expenditures of millions of dollars for development of these space vehicles and their components, extreme emphasis has been placed during the past few years on in-flight reliability. This importance is further emphasized with the carrying of man into space. This has resulted in new controls and new techniques being applied to obtain the desired reliability. Some of the special procedures for the hydraulic components used in such vehicles as the Minuteman, Polaris, Atlas, and Skybolt Missiles are briefly summarized.

Minuteman Auxiliary Power System

The auxiliary power system shown in Figure 3 is used in the control system of the Minuteman Missile. The first stage component has a variable displacement pump that produces 3.7 gallons per minute at 12,000 rpm pump speed. At 3000 psi, this is 6-1/2 horsepower. Similar units of smaller capacity are used in the second and third stages of the Minuteman vehicle, which is shown in Figure 4.

The equipment on this program has a reliability requirement of 0.9998 for a flight duty cycle. Previously, in the normal long life units the test data required to substantiate reliability figures were often of an extremely prohibitive nature in respect to both money and time. However, with many of the more recent missile applications in which a short life time is specified, such as of 100 to 200 hour Mean Time Between Failures, actual testing programs to indicate reliability are now within the scope of available money.

To permit the ascertation of this data within a reasonable time period and at a reasonable cost, confidence factors in the neighborhood of 60 percent to 70 percent are now used instead of the previously dictated 90 percent or higher.

Reliability Management Control

The Minuteman auxiliary power system reliability program consists of a very specialized advanced reliability concept. One of the items on this program that has been given intensive attention is the very extensive management control in respect to reliability. This has included all phases of management including that of manufacturing, engineering, purchasing, and service.

One of the top factors of this phase of the program is an excellent data and information visibility condition for top management to where they continuously have the updated information on the program without having to go through two or three lower echelons to obtain this material.

This has brought about the extensive use of the Program Evaluation and Review Technique (PERT) concept and with even a tailoring of this concept for the specific application.

Figure 5 shows a condensed version of the PERT network used on this program. As many of you are acquainted, the original PERT I Program was event orientated and concerned itself almost solely with scheduling.

The program used here, which is a modification of PERT II, is activity orientated and not only gives major concern for scheduling but also provides for financial control and analysis by management. With it being activity orientated, more detailed PERT charts show a very fine activity scheduling of things that have to be done. With this method it is very difficult to omit something unintentionally during the program. This and other PERT networks are working tools to prepare additional information for management review.

One of the strong points of this program has been very heavy excellent documentation for every sub-phase of this program. This permits a continuous monitoring on a daily and weekly basis and eliminates past difficulties of having to go back through history and document the program from an after-the-fact activity.

This type of action then makes possible correction action by management on a before-the-fact basis rather than on an after-the-fact basis. This is one of the strongest points of this phase of the reliability program. This part of the program has proved extremely valuable when a multi-plant manufacturing activity is involved together with many vendors.

Under the previous conventional methods, information reporting between plants and vendors often lagged by several weeks or several months.

Training

A second major area in the Minuteman APU reliability program has been a very comprehensive training activity. This training activity has been very extensive to cover top management down through all elements of supervision to the actual worker on the job.

One aspect of the training program utilizes motivation training describing to each level their part in the reliability team effort. This has been approached from a weapons systems standpoint. The second phase of the training approach has been through on-the-job training; which not only familiarizes each employee involved with their specific duties, but ensures from a management visibility standpoint the adequacy of skills and necessary procedural instructions so that the product can be produced in a controlled and functional manner.

The training sessions have included movie material supplied by both the prime contractor as well as government sources and actual classroom instruction work.

One of the focal points of the training program is the requirement that all personnel in the major manufacturing areas working on the Minuteman program are certified. This certification comes about only after the intensive training program and upon the completion of passing a written test in respect to this program.

Reliability Through Serialization

Another major phase of this reliability is the serialization program. This program involves the detailed documentation of all major dimensions and metallurgical characteristics of each major part and sub-assembly of the APU.

This detail includes metallurgical melt information on bearing balls, complete documentation on heat treat conditions of various parts, as well as the normal dimensional and hardness information.

With the serialization data, a "baby book" is compiled on each APU having the total information previously outlined. In this book is also the production performance data.

Product Homogeneity

With the centralizing of this total information on each specific component, many reliability studies can then be made with this material. One of the major studies done with this material is product homogeneity. In this program, studies are made to determine the pattern of dimensions produced by the machining process.

This system makes possible the actual location of the most important dimensional and physical characteristics in every APU. The benefit from this knowledge makes most efficient any necessary retrofit involving a minor modification of dimensional or metallurgical characteristics.

By previous method, if a decision was made to field retrofit units with a different part as a result of a dimensional change, it was necessary to disassemble and inspect all units to pick out the specific required units requiring retrofit. With this program units can be immediately identified by serial number for field retrofit.

Analysis Product Uniformity

With this serialization information the analysis of cause and effect that exists between dimensions and characteristics and the performance of the APU can be ascertained by correlation analysis. A relatively new approach to this concept is being utilized with the use of edge coded card multi-factor analysis.

In essence, this analytical technique records characteristic and dimensional data in the form of notches on the periphery of a record card, as shown in Figure 6, while the performance output is recorded on the face of the card. Stacking of the pertinent cards in ascending order of a given performance parameter and analyzing the pattern of notches that result when viewing the edge of the stacked deck permits rapid identification of significant correlation between characteristics and performance. These identified characteristics can then be a topic of a detailed study.

Design Reviews

In addition to the specialized reliability phases outlined above, the normal standard reliability programs are also used. These include such items as detailed design reviews, as outlined in Figure 7.

There are actually three separate design reviews; the first being within the engineering section with a comprehensive review being made by both the Group Supervisor and the Section Head. As outlined in Figure 7, in this phase of the design review there are at least seven reliability check points.

A second design review is made by a design review specialist that reports only to the Chief Engineer. Prior to the release of the design, this specialist is required to sign off the project as being satisfactory from a design and reliability standpoint.

A third review is made by an impartial design review committee made up of not only project engineering personnel, but also representation from purchasing, manufacturing, quality and standards.

Other standard reliability phases include failure mode analysis and apportionment. In this latter work the breakdown of the reliability requirement is made for specific sub-assemblies and specific parts. Also determined in these other phases is the establishment of a vendor supply reliability program and a monitoring of such.

Polaris Missile Motorpump

A second missile hydraulic unit that is receiving considerable reliability attention is the AA-19566 motorpump, which is used in the flight control systems of the Polaris Missile, which is shown in Figure 8. This electric motor driven pump is a variable displacement pump producing approximately 1 gallon per minute flow at 11,400 rpm, and at 3000 psi pressure. This unit, as shown in Figure 9, is driven by direct current electric motor. As indicated in Figure 9, the unit is partially enclosed in a silicone rubber insulation blanket bonded to it for heat barrier properties.

This insulation is left in the uncured state, and cures as it ages. The rubber will withstand approximately 600°F to 1000°F temperatures. One unit is known to have received the direct blast of the nozzle, and saw temperatures over 2000°F, and still operated.

This motorpump development and manufacturing program uses many of the techniques described previously for the previous APS program.

One of the parts of the Polaris reliability program has been a weapon system cost effectiveness philosophy. This program concentrates the reliability dollars in those areas which could yield the highest ratio of reliability improvement per dollar spent. Typical of this part of the program is the use of a visual patch standard in determining the early test phase cleanliness level of the components.

The visual patch standard follows the Society of Automotive Engineers ARP-575 document with certain modifications. This method collects all of the contamination in hydraulic filters after a certain running period, and then has the contamination put on a filter paper. The filter paper then holds the total contamination taken from a system over a specific time period, such as a one-half hour test. The filter paper sample is then compared visually to a standard sample. A typical patch standard is shown in Figure 10. The amount of contaminant collected is determined by visual inspection as to light color differences as well as inspection for individual particles. With this method a system contamination determination can usually be made within one-quarter to one-half hour.

It is only during the final test phases that the more expensive particle count is used in determining final unit cleanliness level. This method uses the SAE ARP 598 procedure, which takes a small sample of hydraulic fluid from a system. This fluid is then filtered through a very fine Millipore filter membrane and the number of individual particles are then counted with a microscope and classified as to size and occasionally type. This type of procedure usually takes several hours. Much of the final assembly and test work of missile units of this type that require a very high degree of cleanliness is done in a clean type room, as shown in Figure 11.

Reliability controls for the operation of this type of room are very strict and require only certified personnel that are familiar with clean room operation to work in this area. This room is typical, in which at least two anti-rooms are used; one for dressing, and the second for vacuuming and cleaning of personnel as they go into the main clean room area. This particular room is completely vacuumed including walls, ceiling, floors, and so forth, each day.

This motorpump reliability program consists, at the present time, of a manufacturing concentration of reliability and analytical approach to meeting the contractually required quantitative reliability measure. This takes form in the utilization of a quality analysis function directed toward ascertainment of marginal and sub-marginal product. This approach utilizes the available state-of-the art

techniques of reliability analysis, as well as many statistical tools.

Atlas Control Pumps

The variable displacement pumps used in the Atlas Missile, Figure 12, program also receives many reliability and cleanliness test phases as previously described.

Working in conjunction with the missile airframe manufacturer considerable development work was conducted as early as 1956 and 1957 in particle counting techniques for contamination control of missile system components. This work actually preceded the present particle count standard ARP 598 by three years. Many of the techniques initially devised for this program later became a part of this cleanliness standard.

Many unique techniques for control system components were used to obtain the rigid cleanliness requirements. These included not only the ultra-sonic cleaning of the components of the control pump, but also included ultra-sonic cleaning of the completely assembled pump and mechanical shaking of completely assembled pumps on a production basis.

This probably was the initial phase and development activity of strict contamination control of missile system hydraulic components in this country. As a result of these unusual cleanliness techniques developed, the component cleanliness level could then be confirmed by the missile manufacturer upon receiving the component, as well as it being determined and maintained during a number of missile system check-outs.

In addition to the normal engineering qualification and reliability monitoring tests, search for critical weakness tests are conducted on these control pumps under operating conditions that often exceed the previous engineering qualification phases by a factor of two.

The reliability for the controls of this missile have received additional inputs as a result of the Mercury space flights. All of the Mercury missile components, including the control pumps, are given special groups of inspections and tests in addition to those received in the normal Atlas program. These include not only additional dimensional and metallurgical inspections, but include a large number of functional tests. There is a major reliability review and analysis of the hydraulic components by serial number, which is maintained throughout the life of the unit in the Mercury program.

Skybolt Hot Gas APU

As an extension of hydraulic controls for space vehicles, study and development of hot gas servo and actuating systems has been underway at Vickers for the past approximate six years.

These hot gases are used to drive a gas motor similar to a hydraulic motor, which then directly drives a hydraulic pump, thus providing hydraulic flight control power.

These hot gases are obtained by a number of means such as either bleeding off the main rocket engine or using a solid propellant gas generator. It is this latter case that is used in the Skybolt system, as indicated in the circuit drawing in Figure 13. As indicated, a solid propellant is ignited producing hot gas which motorizes the piston motor, which then mechanically drives the hydraulic pump.

Figure 14 shows a cutaway of the hot gas motorpump. As indicated, this is an integrated package, with the gas section on the right. This particular device will produce a 12 gallon per minute flow for an initial peak period and then be reduced to approximately half of this figure for the remainder of the run at 3000 psi hydraulic pressure. The total operating time is something less than 2 minutes for this APU in this Skybolt application, which is shown in Figure 15.

With the aspect of combining hot gas controls with the more standard hydraulic controls and the more limited life aspect, additional changes in the standard reliability program are made to obtain the greatest benefit from the expenditure.

While we can draw upon twenty-five years experience for reliability studies in the hydraulic section of this APU, in the gas section reliability analysis failure is done on a different basis.

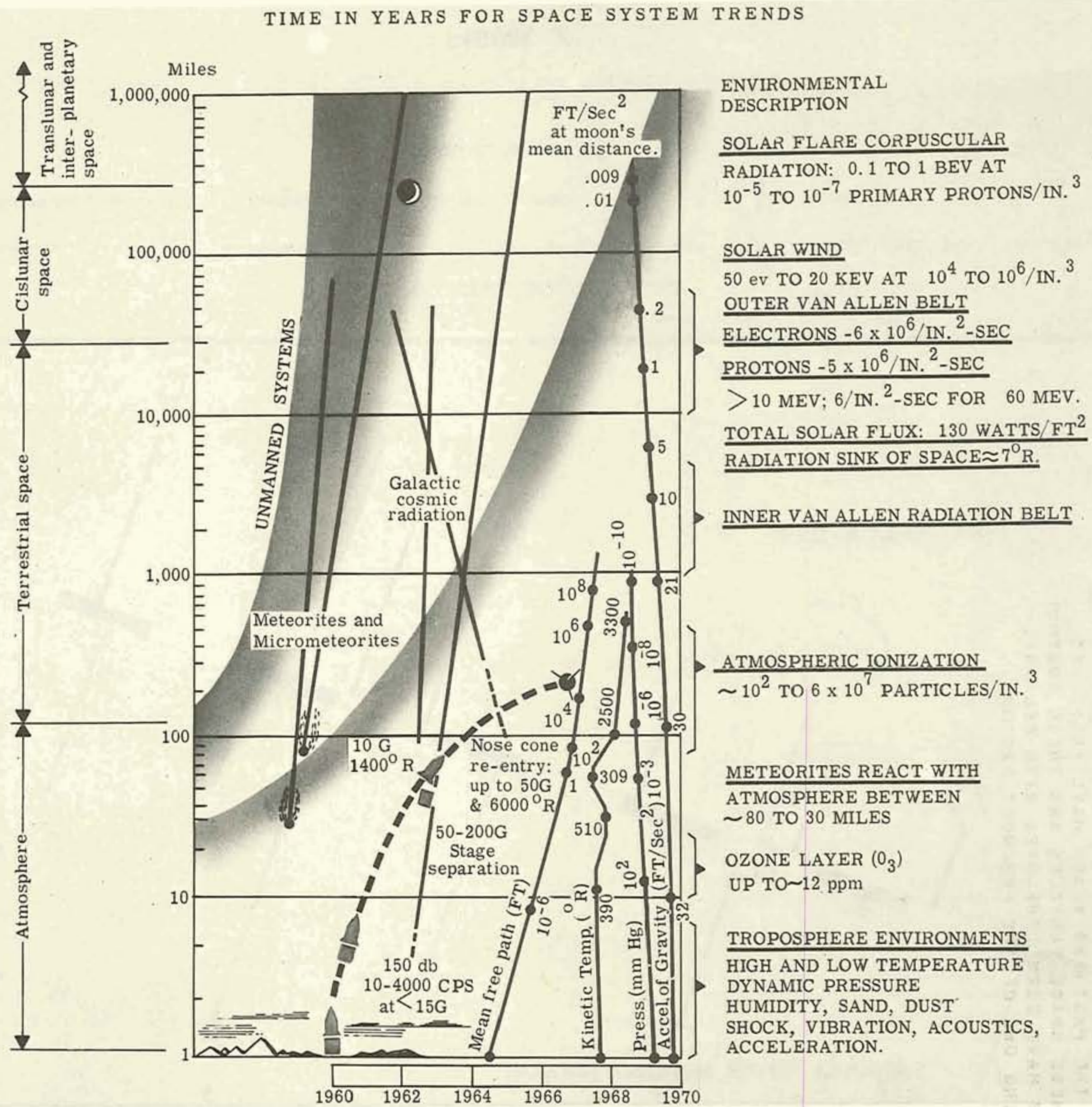
With a unit of this type, as shown in Figure 16, which shows the disassembled view, gas temperatures up to 2000°F are used through the burning of the ammonium nitrate propellant. In a reliability program of this type extreme attention is given to the selection of high temperature materials.

Summary and Conclusion

Studies and developments of space vehicle control systems during the past few years have indicated that reliability of these systems must first be designed into the equipment, and then through continued monitoring be built into the equipment.

IN SUMMARY, I WISH TO SAY THAT RELIABILITY STUDIES COULD AND SHOULD BE BASED UPON AS MUCH PAST EXPERIENCE AS POSSIBLE; BUT IN OUR RAPIDLY CHANGING SPACE TECHNOLOGY THIS IS ALWAYS THE FIRST STEP ONLY, AND IT IS NECESSARY TO TAILOR RELIABILITY STUDIES AND ACTIVITIES FOR EACH NEW CONCEPT AS IT IS DEVELOPED.

I BELIEVE AMERICA'S SPACE EXPLORATION DURING THE PAST TWO YEARS HAVE INDICATED THAT THESE SPACE VEHICLES AND THEIR CONTROL SYSTEMS HAVE BEEN DEVELOPED WITH RELIABILITY BEING ONE OF THE FOREMOST FACTORS.



SUMMARY OF SPACE ENVIRONMENTAL CONDITIONS

FIGURE 1

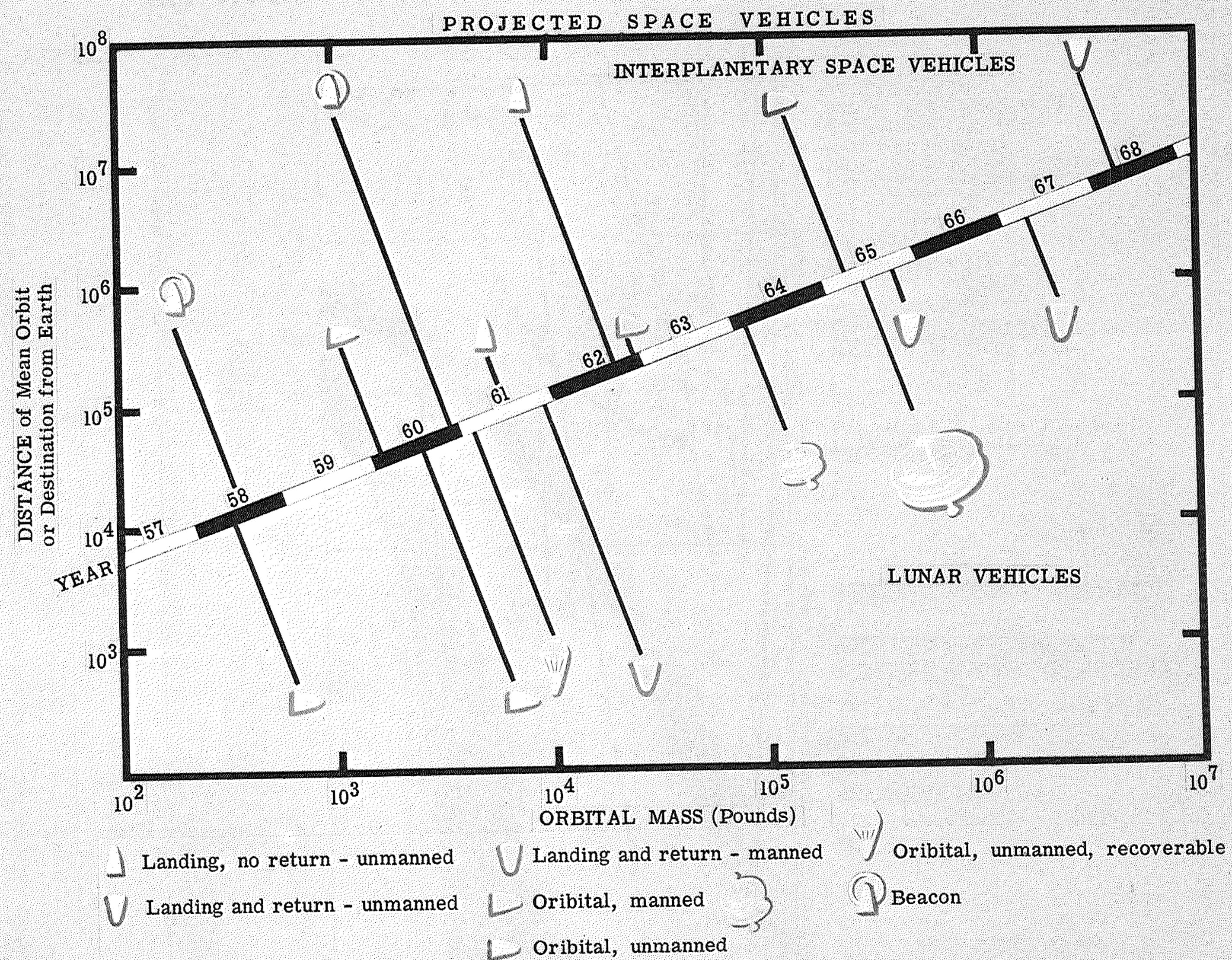
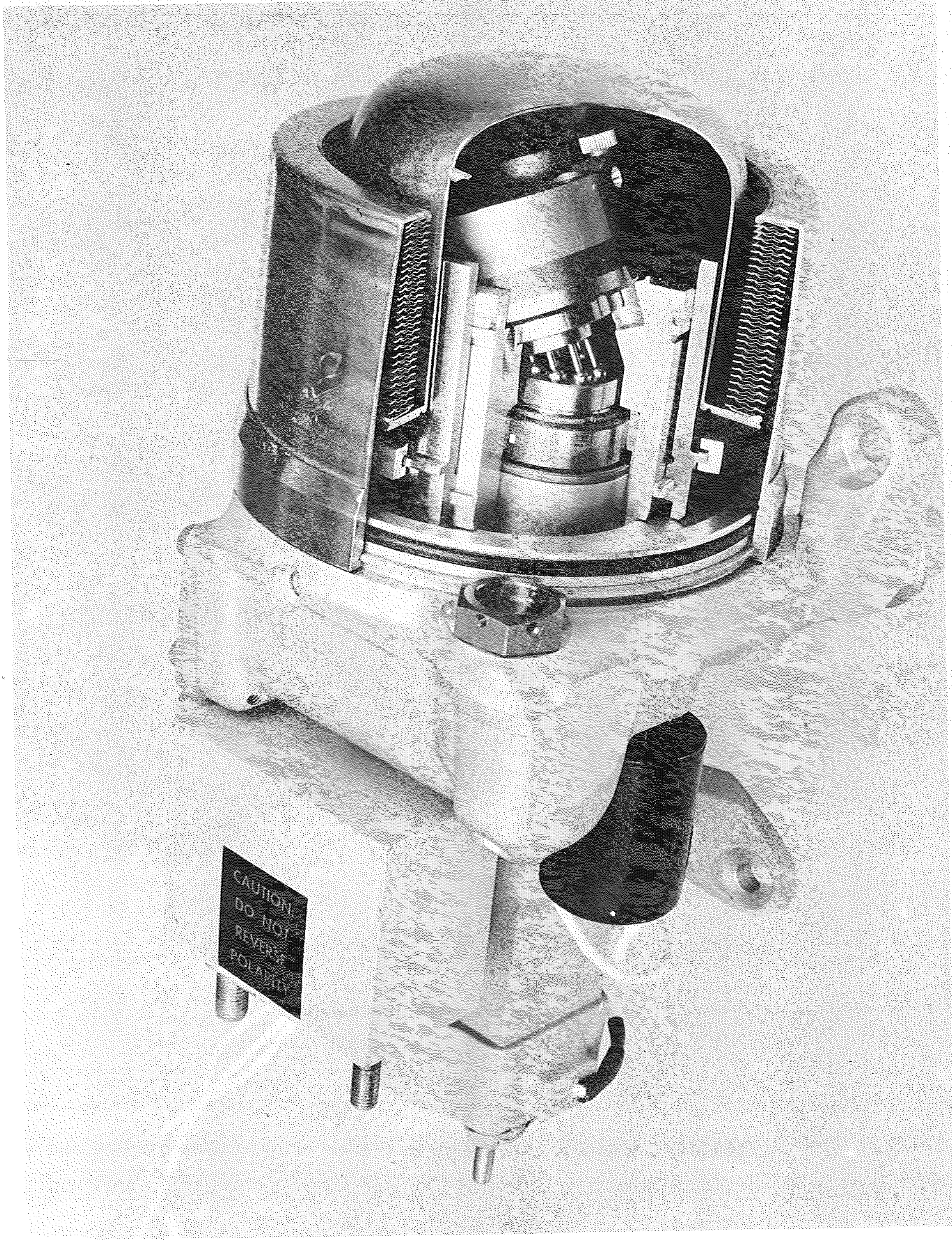
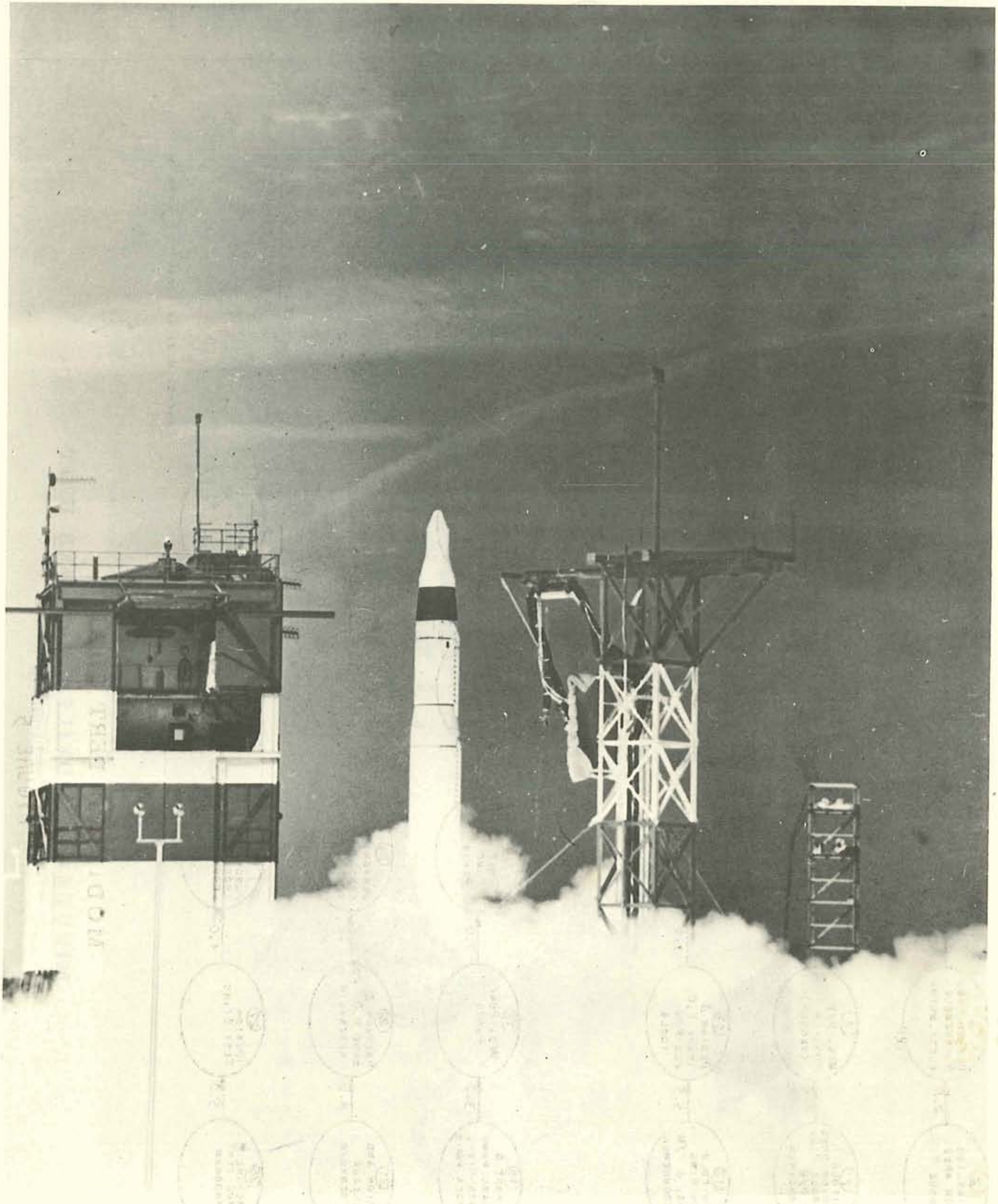

PROJECTED SPACE VEHICLES
INTERPLANETARY SPACE VEHICLES
LUNAR VEHICLES
DISTANCE of Mean Orbit or Destination from Earth
YEAR
ORBITAL MASS (Pounds)
57
58
59
60
61
62
63
64
65
66
67
68
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Landing, no return - unmanned
Landing and return - unmanned
Landing and return - manned
Oribital, manned
Oribital, unmanned
Oribital, unmanned, recoverable
Beacon

FIGURE 2



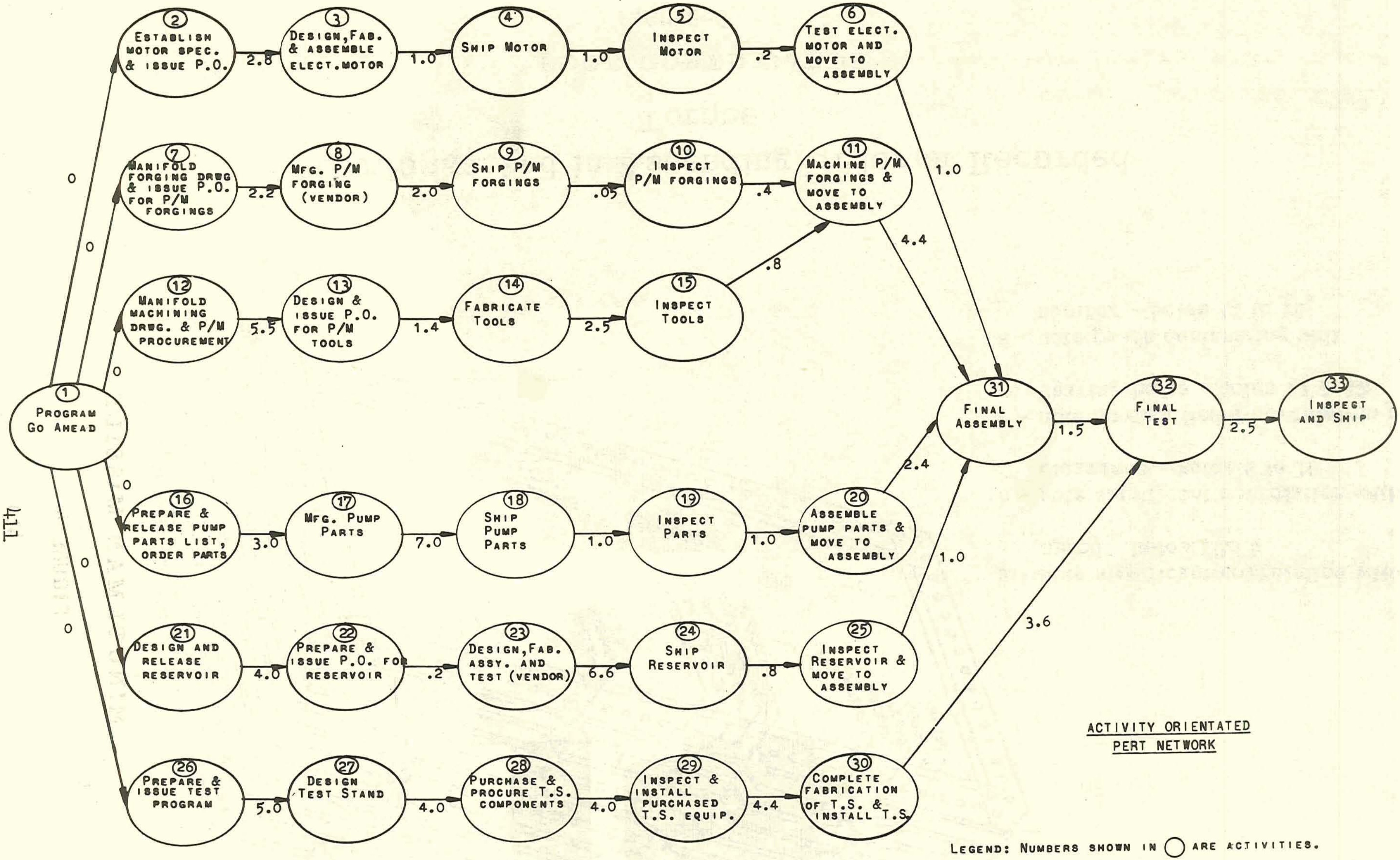
MINUTEMAN AUXILIARY POWER UNIT

FIGURE 3



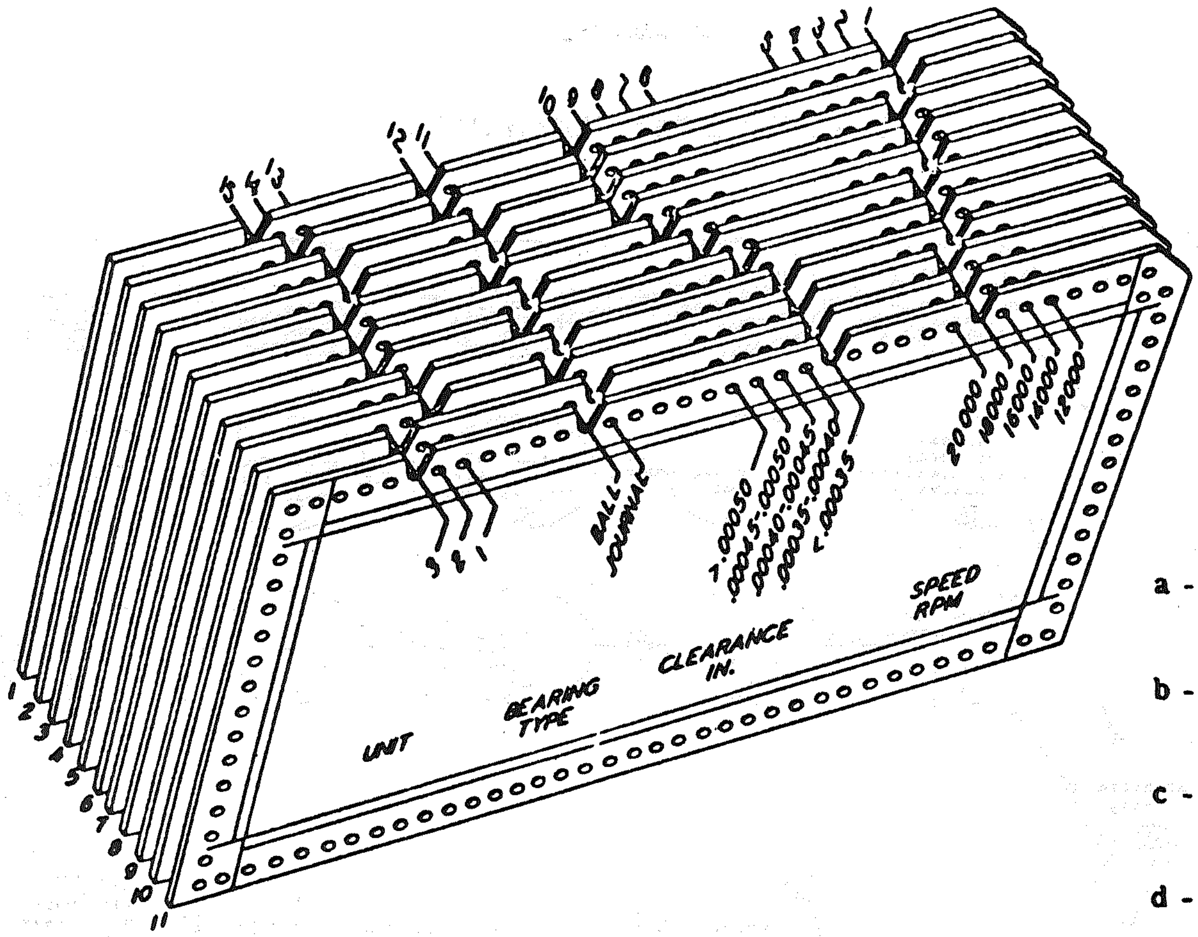
MINUTEMAN MISSILE

FIGURE 4



MODIFIED PERT CHART

FIGURE 5



a - note significant correlation with speed - holes 1 to 5

b - note significant correlation with clearance - holes 6 to 10

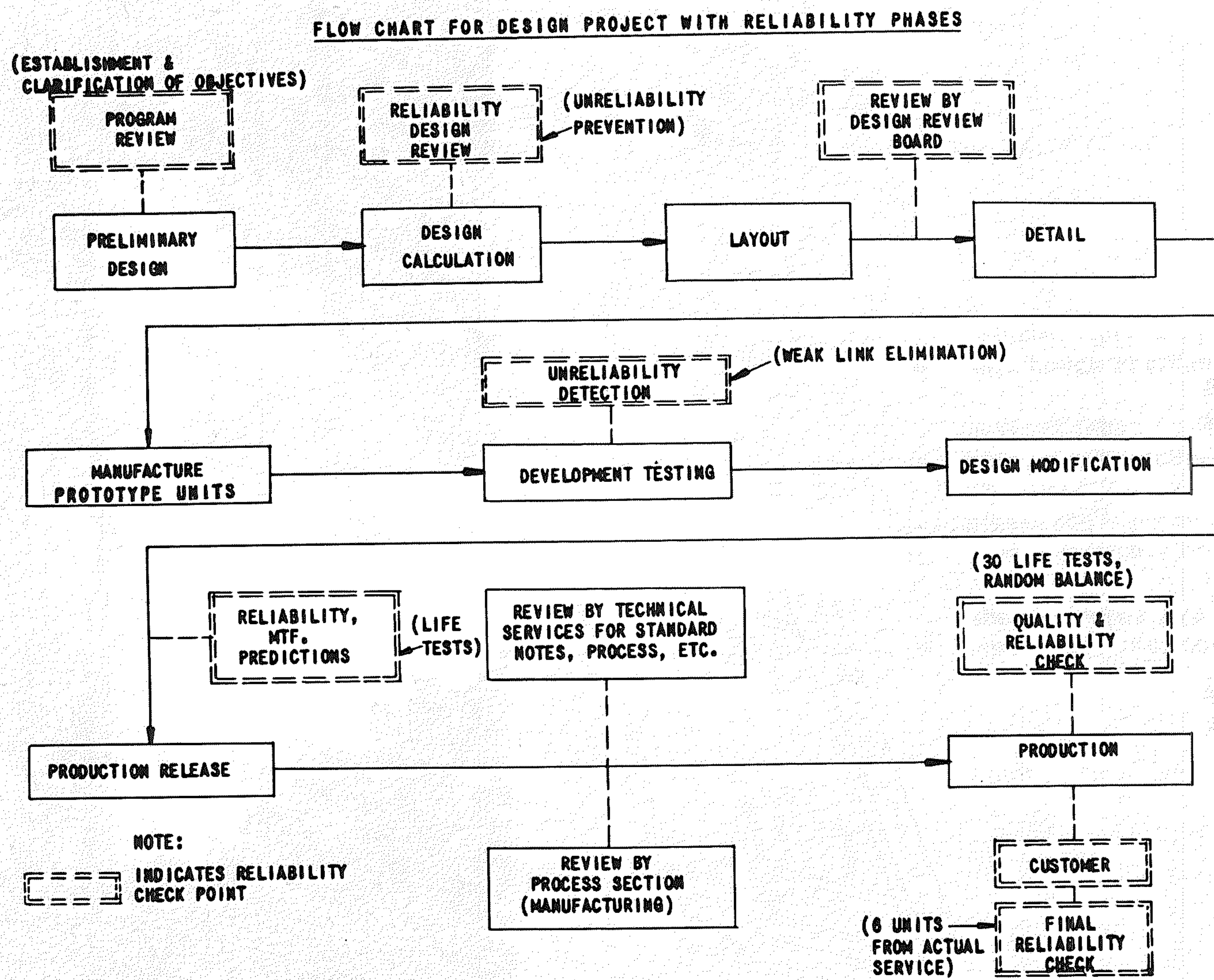
c - note no significant correlation of bearing types - holes 11 & 12

d - note punch designating unit number - holes 13 to 15

Cards Stacked in Ascending Order of Recorded Torque

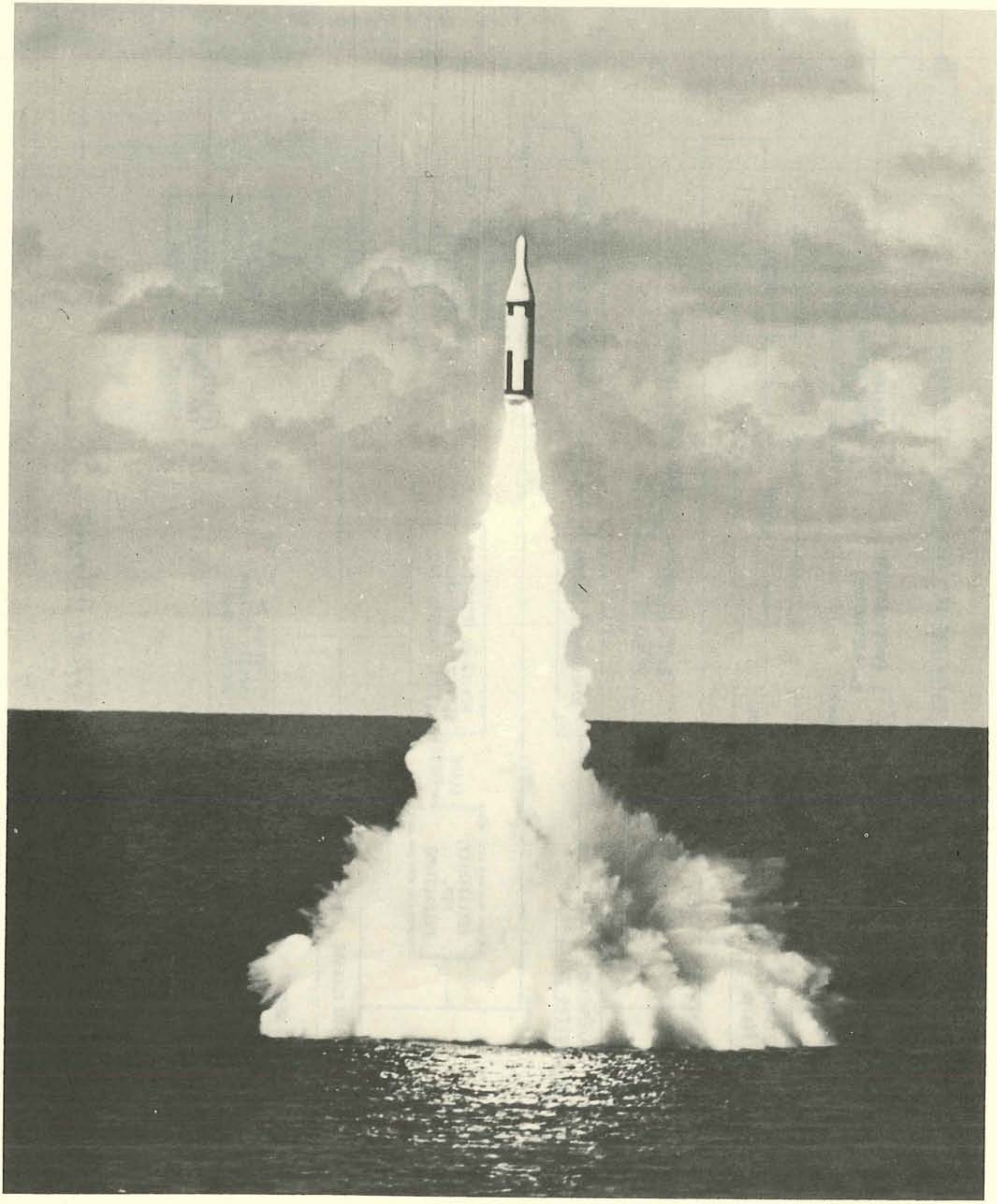
EDGE CODED CARDS

FIGURE 6

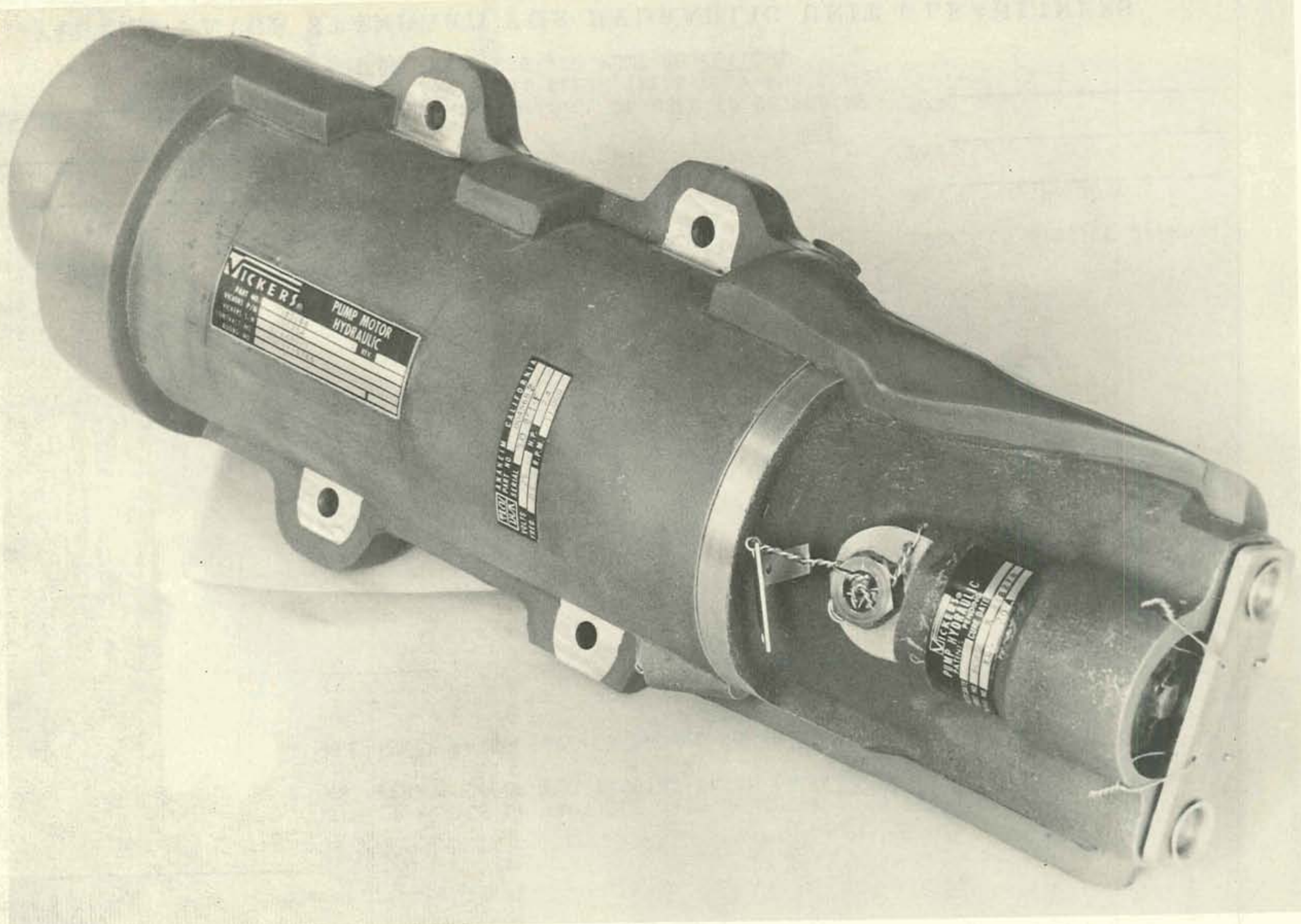


DESIGN REVIEW CHART

FIGURE 7



POLARIS MISSILE
FIGURE 8



POLARIS MISSILE MOTORPUMP

FIGURE 9

DUPLICATE NO. 2

ENGINEERING PATCH STANDARD

V.P.S. NO. 1009-A

FIRST USED ON MODEL NO. AA-19552

FIRST USED ON T.P. NO. 3217

4-15-60

STRICT NOTICE OF PARTICLE SIZE IS TO BE USED, AS WELL AS AVERAGE COLOR FOR PASSING PATCH SAMPLES.

ALL INLET PATCH SAMPLES SHOULD BE AS SHOWN BELOW.

	1ST PATCH	FINAL PATCH
OUTLET --		
CASE DRAIN --		

AVERAGE INLET PATCH

VICKERS APPROVAL

BY: A. B. BILLET 4-19-60

BY: J. BARTA 4-19-60

BY: C. LOSEY 4-20-60

LOCKHEED MISSILE APPROVAL

BY: J. P. BOWERS

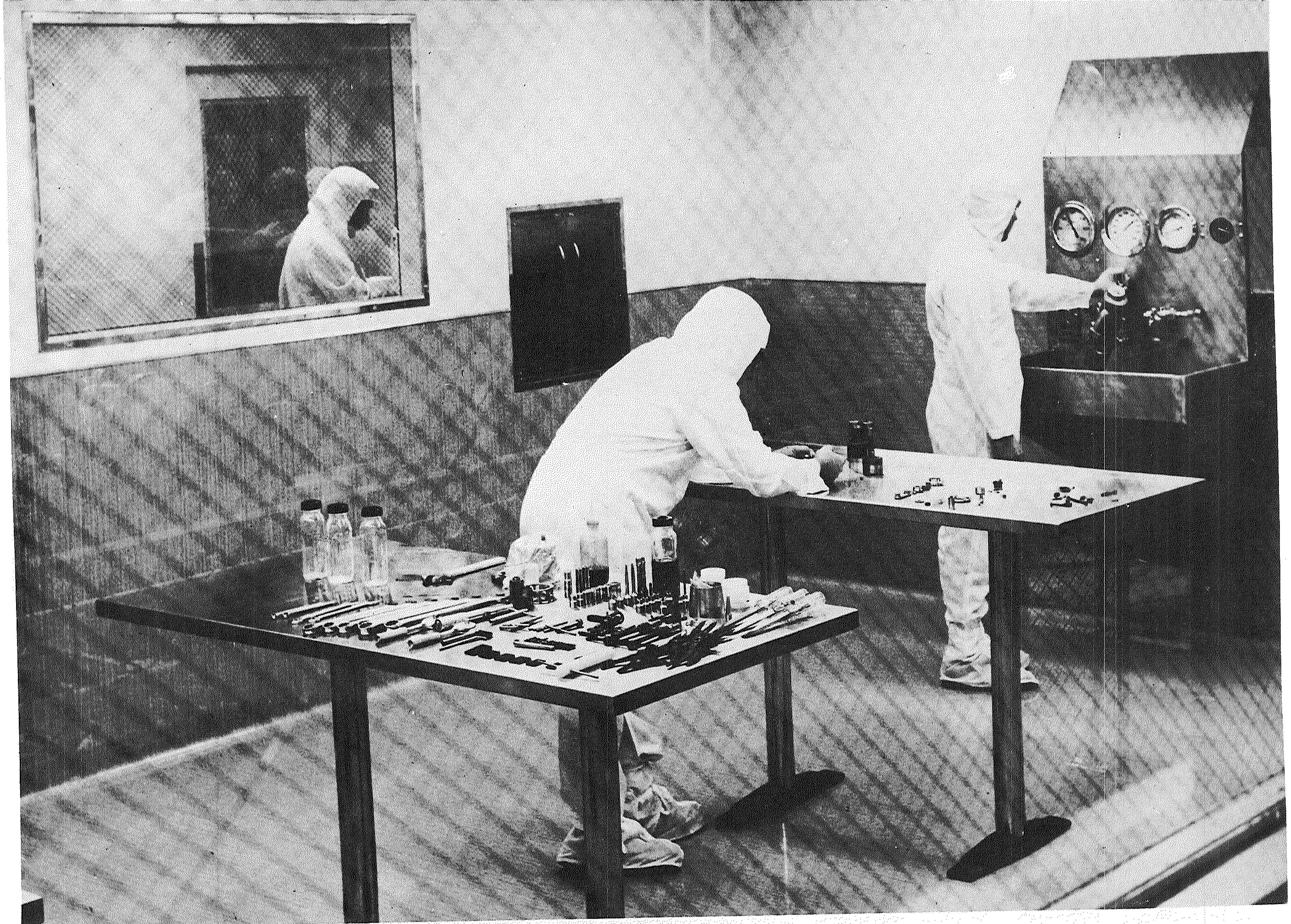
BY:

BY:

THE INLET PATCH SHALL BE USED TO DETERMINE TEST STAND FLUID CLEANLINESS ONLY AND SHALL NOT BE THE CAUSE FOR PUMP REJECTION.

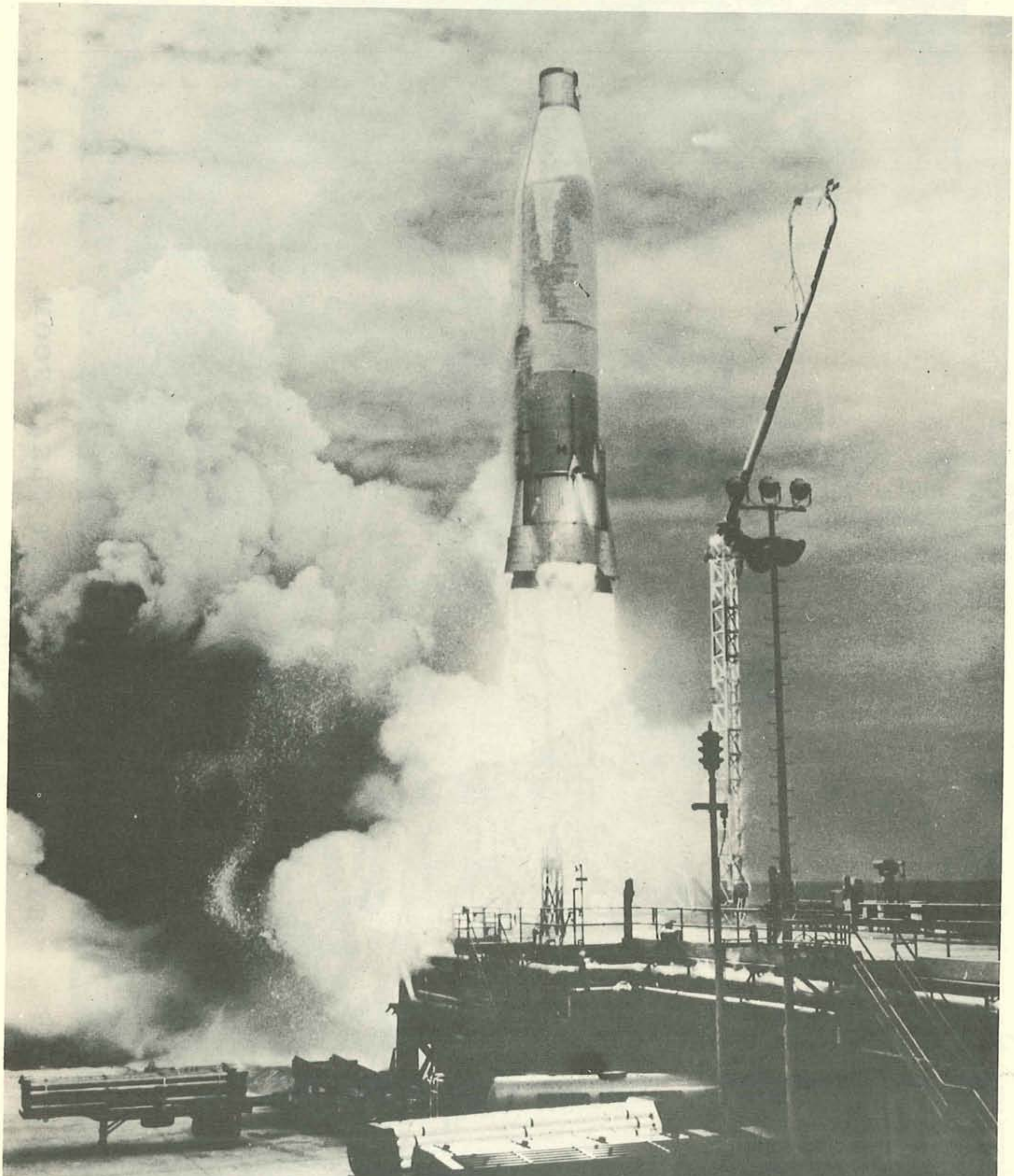
FILTER PATCH STANDARD FOR HYDRAULIC UNIT CLEANLINESS

FIGURE 10

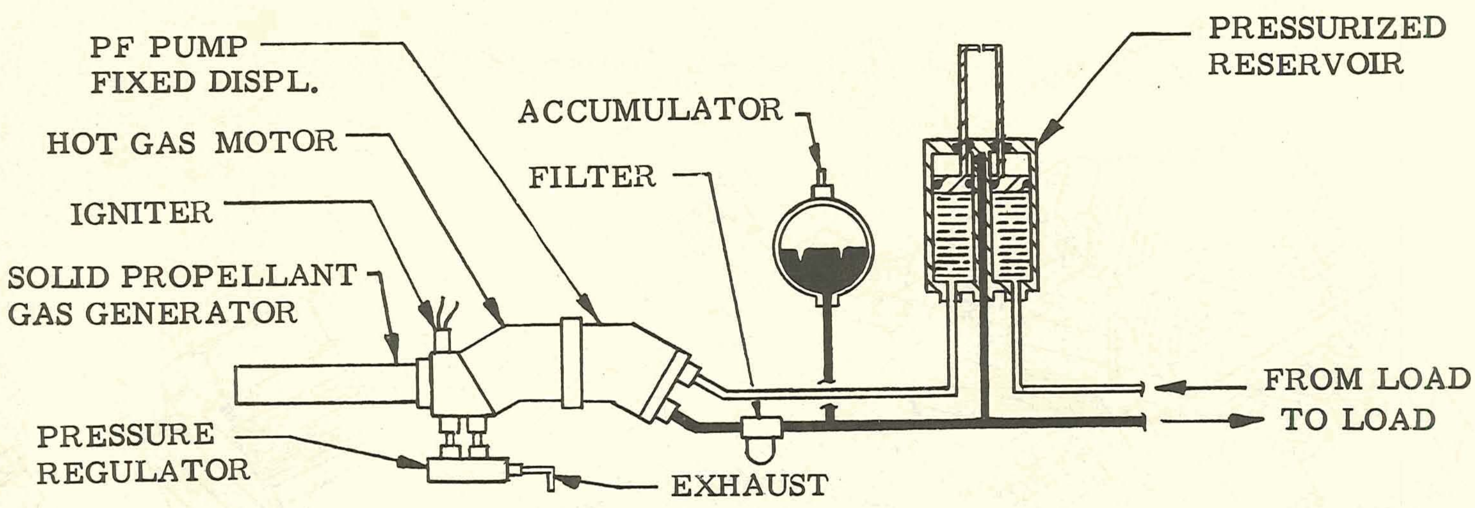


HYDRAULIC COMPONENT CLEAN ROOM

FIGURE 11



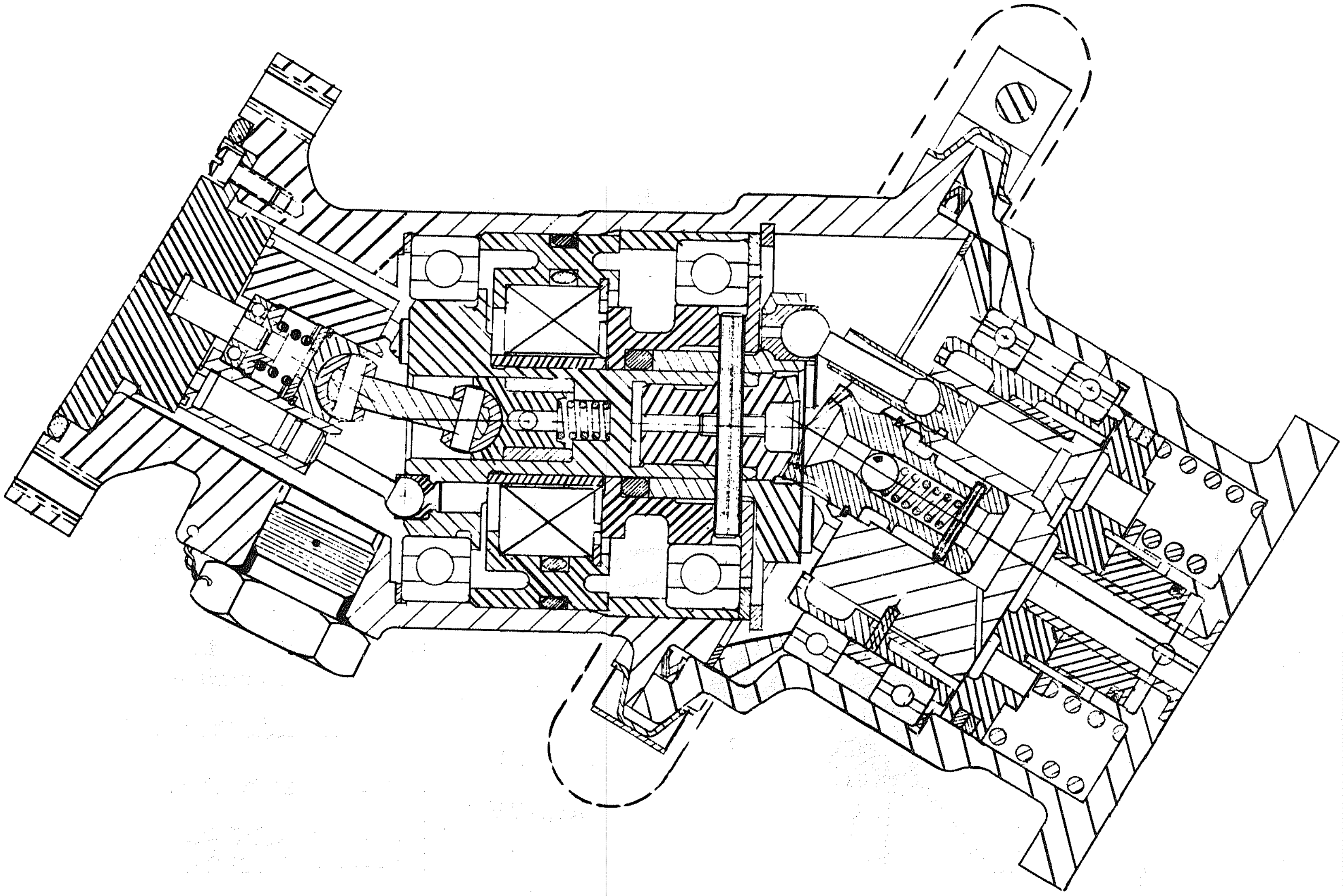
ATLAS MISSILE
FIGURE 12



Gas Regulator Type System

HOT GAS SYSTEM CIRCUIT DIAGRAM

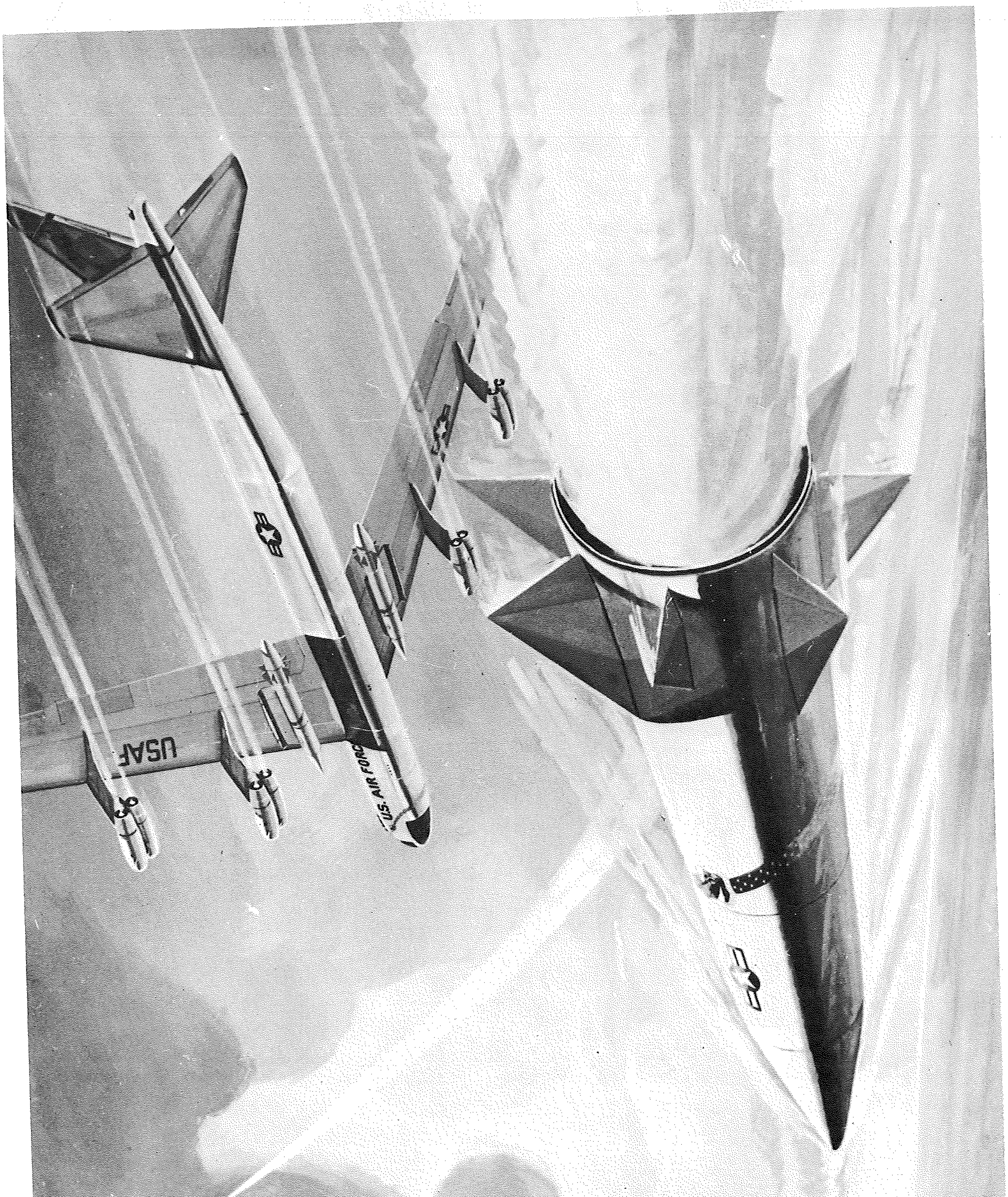
FIGURE 13



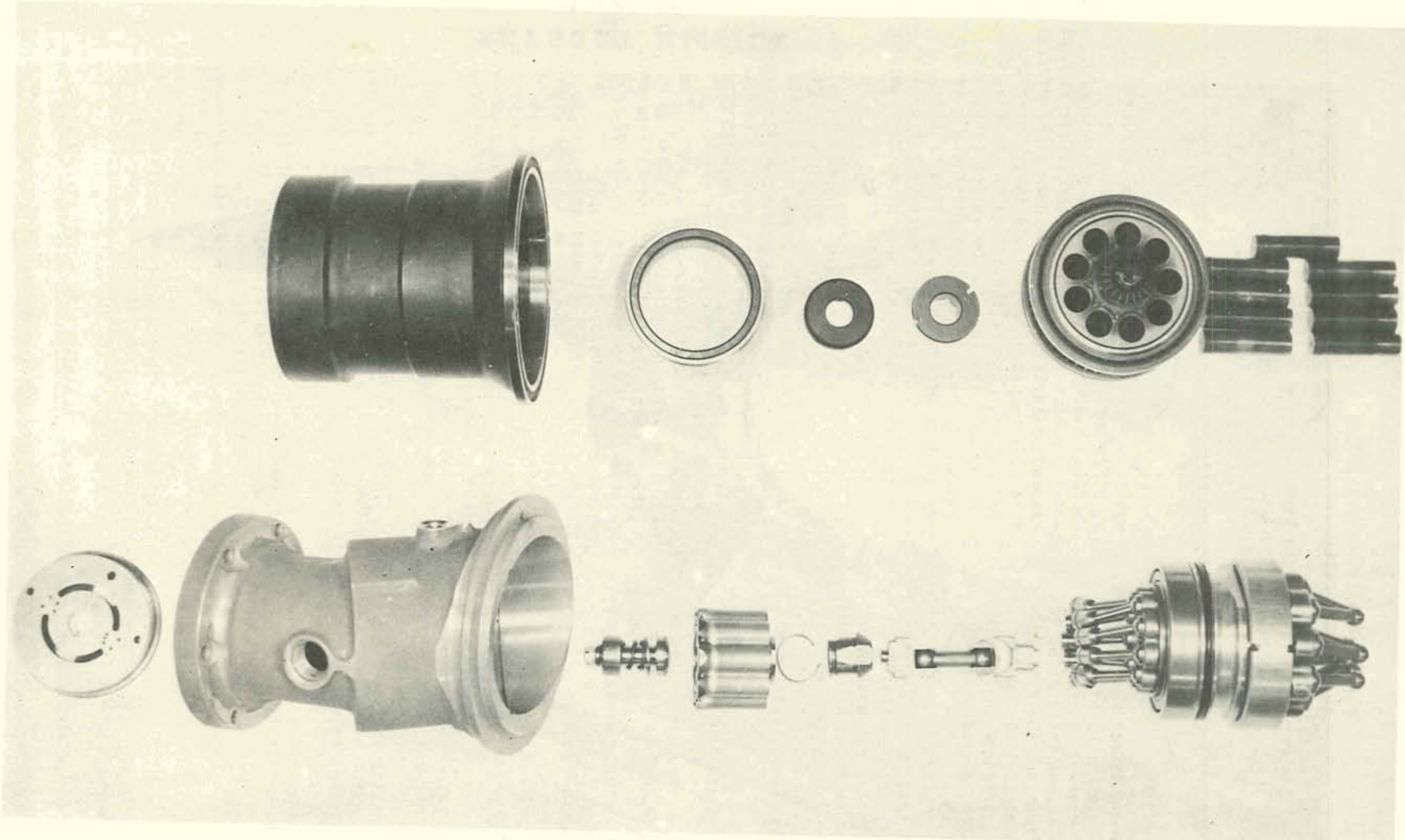
Cross Section Drawing GAM-87A (Skybolt)
Hot Gas Motorpump

CROSS-SECTION VIEW OF HOT GAS MOTORPUMP

FIGURE 14



SKYBOLT MISSILE
FIGURE 15



DIS-ASSEMBLED HOT GAS MOTORPUMP

FIGURE 16

RELIABILITY IN PROCUREMENT
F-105 AIRCRAFT ELECTRONIC SYSTEMS

Arthur P. Coletta
Joseph A. Cravero
Charles W. Russell

Republic Aviation Corporation
Farmingdale, New York

The space effort has emphasized the importance of having reliable equipment by highlighting the cost of failure. However, there is really little difference between the cost of low reliability in a space effort and the cost of low reliability in an operational manned weapon system. The intense realization of this cost in a space effort is due to the concentration of loss in one dramatic failure.

Design of new weapon systems now includes reliability orientation, but the initial design of many existing weapon systems did not include reliability orientation as we think of it today. The requirement for a specific, proven reliability under a specific environment was not generally included in the procurement contracts for high volume production.

Studies generated to suggest means of improving the reliability of existing equipments have shown that the cost is very high. The result of the improvement has been expressed as benefits which include reduction in maintenance requirements and improvement in probability of completing a mission; but it is questionable whether the benefits have ever justified the cost of improvement in terms of dollars and cents, the terms most understood by the management who must make the decision to expend the required funds.

This paper describes a technique, applied to an existing production program, which justifies the cost of reliability improvement by expressing the resulting benefits in terms of dollars and cents and also studies the sensitivity of the estimated savings to variations in the basic assumptions. This makes it possible to evaluate the program in terms of an investment having specified risks and a significant return, bringing it closer to a strict management-accounting type of decision.

INTRODUCTION

In the discussion of Reliability at symposiums and in literature, certain axioms have been emphasized many times. Two of these are:

1. reliability must begin with design, and
2. reliability adds to initial cost but reduces maintenance cost.

These axioms were substantiated in a program recently completed at RAC. Techniques of estimating savings due to reliability improvement, so often advocated in general terms, were applied to a specific production program with results indicating that high reliability returns tremendous savings to the customer. The program that will be discussed had one large drawback, and that is, despite the estimated savings, the program came too late in the weapon system procurement cycle. If the considerations given to the subject program had been given to the original design and procurement of the various sub-systems, the overall savings to the customer would have been much greater.

In the case of the F-105 Weapon System, the original specifications for both GFE and CFE electronic systems were written early in the past decade, omitting the present emphasis on specific reliability requirements. The Aircraft Industry received its greatest impetus to apply specific reliability efforts at the Santa Barbara Reliability symposium in 1957. There is, of course, no definite proof that such effort, initially applied to the F105 electronic systems, would have resulted in systems with presently achieveable reliability. However, it is felt that formal reliability analysis, design review procedures and reliability demonstration testing would have resulted in more reliability in the early systems. In all fairness to the equipment manufacturers,most of the F105 electronic equipment was, even in the early stages, considerably more reliable than similar systems of comparable complexity.

The reliability problem associated with these complex integrated electronic systems is well known. It is the problem created by the product rule which requires that a high degree of reliability be achieved in each individual system to assure sufficient reliability of the integrated electronics system. It became apparent very early in the production of the F105 that to achieve the required effectiveness of the weapon system, the reliability of the integrated electronics system should be increased, while the non-electronic systems evidenced an acceptable reliability growth and therefore did not require an intense improvement effort.

RELIABILITY IMPROVEMENT PROGRAM

The subject program, designated "RIP", involved:

1. the determination of the optimum MTBF

that could be obtained in the various systems,

2. the solicitation of technical and cost proposals from the various affected suppliers, and

3. the analysis of the reduction in spares and repair costs that would result from this improved MTBF.

Of course there are other reasons for improving reliability, for example, to improve mission completion capability. However, if reliability is designed into the system to minimize operating expenses during peacetime operation, a high mission completion reliability will normally result. Most of you are involved in designing and building systems which, it is hoped, will spend their useful lives in defending the peace. If the reliability job is done adequately for this purpose; that is, the equipment is designed to be reliably stored, transported, ground checked, flight tested, etc., not only will it pay off economically, but the reliability potential will be of sufficient degree to satisfy mission requirements.

Economics of Reliability

The exact relationship of reliability to economics is difficult to determine. You are undoubtedly familiar with the general reliability cost relation which has been published many times in the past (Figure 1). As reliability is increased, the initial cost will increase to some point where further improvement could only be obtained at tremendous cost. Similarly, as reliability is increased, the cost of maintenance support is reduced to some point where further increase in reliability has a negligible effect in the reduction of maintenance cost. The total cost is represented by the curve plotted from the summation of the first two curves. The optimum is the low point of the total cost curve, where maximum reliability is obtained for the lowest cost.

If improved reliability can have a beneficial effect, then low reliability can have an adverse effect. Low reliability affects the prime and sub-contractor by increasing:

1. testing required before acceptance,
2. equipment removals during the manufacturing process,
3. repairs and maintenance at the factory,
4. stock requirements during manufacture,
5. production flow time,
6. field liaison, and
7. obligation of rework under contract warranty clauses, or loss of profit under contract incentive-penalty clauses, each of which increases production costs.

Low reliability affects the customer by increasing:

1. spares requirements,
2. repair facility requirements at the base and depot levels,
3. manpower requirements, and
4. quantity requirements for critical skills.

Each of the above reduces weapon system utilization rate and the probability of completing a mission.

F105 Integrated Electronics

The integrated electronics system of the F105 consists of seven individual electronic sub-systems:

1. Auto Pilot
2. Doppler Navigation System
3. CIN
4. All Attitude Reference System
5. Integrated Instruments
6. Central Air Data Computer, and
7. Fire Control System.

In the discussion that follows, MTBF figures have been altered to avoid security violations; changes have also been made in the cost figures to avoid disclosure of proprietary information. The paper describes the technique used to estimate the magnitude of savings that can result from achieving high reliability in the equipment. The exact information can be made available upon request through proper channels.

Figure 2 lists the MTBF of each system when the program was initiated in January 1961; and the MTBF that was expected to be achieved thru normal growth by July 1963, such growth being attained through the normal changes to the system resulting from ECP's, etc. Also indicated in this figure is the ultimate MTBF goal that was desired for each of the various systems. This goal was established to achieve a 98% reliability of the integrated electronics system for a 2 hour mission with all subsystems operating. It should be noted that this requirement does not reflect a mission completion requirement since redundancy within systems and redundancy between systems would become applicable. However, full operation of all subsystems is a requirement of the contractor for delivery of the weapon system. Therefore, a goal was established to have no more than two failures in the electronic systems out of every 100 production flight tests.

The Mean Time Between Failures allocation to the various subsystems was based on system complexity, state of the art in the development of the system, and the effect that each subsystem has on the mission completion capability of the aircraft.

Ground Rules for Improvement

The next step in the program was to contact each of the equipment vendors (seven GFE and one CFE), in regard to improving the reliability of

each of the systems. Certain ground rules were established, which limited the type and degree of change that could be made.

1. Each of the vendors was requested to provide cost and schedules to achieve 100%, 75%, 50%, and 25% of the ultimate MTBF goal.
2. Any improvement in reliability would have to be available for installation in the aircraft 18 months after contract.
3. The redesigned systems must be interchangeable with the existing systems; i.e., no major aircraft redesign required.
4. Any MTBF that was predicted would have to be demonstrated by an environmental test similar to AGREE but modified to represent F105 requirements.

Each of the vendors submitted proposals to accomplish the improved reliability giving costs and schedules to achieve various levels to permit analysis of cost vs. reliability trade-offs. The level that was selected for each of the various systems is shown in Figure 2. These levels were selected after analyzing each proposal for its effect on costs, schedules, overall capability of the weapon systems, and the probability of attaining the level specified. In some cases, higher MTBF levels could have been obtained at the expense of reducing weapon system capability or at the expense of considerable redesign of the aircraft and AGE.

Having considerable operational experience with these systems provided the prime and subcontractor with some advantages in this program. One of these advantages was that there were considerable data available to indicate the areas in each system that should be redesigned or modified for reliability improvement.

Improvement Techniques

In addition to certain specific improvements, most of the sub-contractors followed the general approach shown below:

1. Use of higher reliability piece parts.
2. Elimination of adjustments and trim pots.
3. Replacement of tubes with transistors.
4. Incorporation of circuit redundancy.
5. Simplification of many of the circuits.
6. Performing environmental type reliability tests.
7. Greater derating of piece parts.

Effect on Reliability

A comparison of system reliability, before and after improvement, can be seen in Figure 3. This chart indicates the reliability of each individual system, for a two hour mission, and the overall reliability obtained from the product of the reliability of the individual systems. The total reliability in January 1961 was about 59%, the predicted growth reliability was 78% and the reliability that would result from the Reliability Improvement Program is 90%.

PROGRAM MANAGEMENT

In a program such as this, the weapon system prime contractor (Program Manager, Figure 4) must

1. furnish all statistical failure data available that will aid in selecting areas in need of improvement:
2. monitor all tests that are required,
3. prepare equipment specifications regardless of whether the affected equipment is CFE or GFE,
4. co-ordinate the preparation of test bulletins, operations sheets, technical orders, etc. to assure that changes to the systems are conveyed to maintenance and operating personnel as well as factory personnel;
5. evaluate reliability demonstration tests,
6. standardize on a time and failure reporting program for all vendors,
7. assure compatibility between the improved electronic system and the airframe, and
8. monitor equipment in the field.

It is particularly important that interacting systems be fully tested and integrated prior to installation in the airframe. Every production program has a carefully planned delivery schedule; changes must not be introduced that would delay that schedule. Strict attention to details must be maintained, since very often newly designed or modified units can cause more difficulty than the original units. A program as complex as the Reliability Improvement Program therefore must have close coordination and thorough reliability testing.

JUSTIFICATION

The cost of such a program is justified in terms of benefits either directly or indirectly related to dollars.

In analyzing the benefits to any supplier (prime or sub-contractor), they may be separated into three general categories; Dollars, Reputation, and Product. The improvement in reliability affects production costs, generally results in a less expensive but always improved product which in turn improves the contractor's reputation for production of highly reliable equipment.

To the customer, improvement in reliability of the integrated electronic systems will have a beneficial effect in several areas, all of which reduce the cost of fleet support. In general, the areas which benefit include the following:

1. Peacetime spares requirements are reduced, together with repair facilities and personnel workload.

2. Personnel requirements are reduced, favorably affecting quantity requirements for critical skills.

3. War reserve requirements are drastically reduced while maintaining at least the same fleet support capability as without the improvement in reliability.

4. Size and weight of flyaway kits are drastically reduced, resulting not only in a decrease in cost but an increase in fleet mobility while maintaining the same support capability.

5. Aircraft utilization is increased and turn-around time reduced resulting in more aircraft in serviceable status with the same maintenance effort or the same number of serviceable aircraft attained with less maintenance effort.

6. The probability of successfully completing a mission is increased.

The basic "ground rule" for this study has been that the non-recurring cost of implementing such a program must be recoverable within 2 years through the resulting savings in peacetime spares requirements, less recurring costs.

No benefits other than peacetime savings in spares have been considered. The limitation to peacetime savings was made after an attempt to obtain data for the determination of savings in war reserve materiel indicated that no one acceptable technique for requirements computation could be established. Similar problems were encountered in attempting to investigate savings in personnel, warehousing, and transportation. It is obvious that limitation of estimated savings to peacetime spares leads to a conservative estimate of total savings to the customer.

The cost of reliability improvement effort to be applied to individual systems was optimized by comparing the potential peacetime savings with program cost. The entire package was then reviewed to assure that the total savings for improvement in reliability was sufficient to recover, within two years, the cost of implementing the program. The sensitivity of estimated savings to (a) reduction in total equipment operating time and (b) partial accomplishment of predicted reliability improvement was also prepared to indicate systems most likely to contribute substantial savings in peacetime spares.

Logistics

Annual reports of the Air Force Spares Study Group outlined in general the effect of present war plans on logistics requirements. Implicit in the war plan is the concept that any future war will be fought with materials, weapons, and resources "in being" and deployed with combat forces. As a result, it has been decided to implement this concept with a drive to improve base self-sufficiency, minimize the base and depot repair cycles and improve aircraft utilization. Each of these goals must be accomplished in peacetime in preparation for a war situation.

The improvement of base self-sufficiency and repair cycle time is primarily an Air Force in-house problem which can be considerably enhanced by the various manufacturers through simplification of airborne equipment and the incorporation of maintainability principles. Every effort should be made to improve maintainability at the same time that an improvement in reliability is incorporated through redesign. However, the benefit gained from increased base repair capability was not considered in calculating the resulting savings in support requirements.

The improvement in aircraft utilization is very definitely affected by an improvement in reliability (or mean time to failure), since the number of equipment failures is directly reduced.

Peacetime Stock

Neglecting War Reserve Materiel, the stockage objective consists of a peacetime stock level (Operating Stock Level) sufficient to maintain the fleet in planned peacetime activity for a period of 45 days without regard to reparables returned. In addition to the stock level, the supply pipeline must be full in order to achieve a constant return flow of reparables to the using command (Operating Requirement). The purpose of the peacetime stock level is to absorb any sudden fluctuations in demand due to an unanticipated increase in flying activity or a sudden decrease in the flow of reparables returned.

Sensitivity of the number of spares in the supply pipeline (Figure 5) to an increase in MTBF is dependent upon the base repair capability associated with the particular component to be repaired. Spares requirements for components with a low base repair capability are extremely sensitive to an increase in mean time between failure, resulting in extensive savings.

Items in the repair pipeline not only add to peacetime costs but are useless in the present war concept which depends upon materiel and forces "in being". The number of items in the supply pipeline can be reduced by increasing base repair capability, reducing repair cycle time, or increasing MTBF.

The peacetime stock level, which does not consider reparables returned, is inversely related to mean time betweeen failure. For example, if MTBF is doubled, the peacetime stock level can be cut in half.

The repair pipeline and the peacetime stock level, then, are two fertile areas for potential spares savings.

The technique used to estimate the savings in peacetime spares is based upon an analysis

which does not consider random variation in demand for spares. This does not materially affect the accuracy of the analysis, since the failure rate base was Mean Time Between Failure, resulting in an estimated demand which is a mean for the random variation. As a result, the indicated savings for the first quarter shown in the sample computation below, may not be realized the first quarter.

Conservative Estimate

The components under investigation are limited to major sub-assemblies only (black box level). That is, the savings in requirements for spare modules (lower than black-box level) was not included. In addition, it was assumed that the condenmation and wearout rates were sufficiently negligible (less than 1%) that omission of these requirements would have little effect on the final result.

The omission of spares support requirements for

- base pipeline
- equipment lower than black-box level
- equipment condemned
- equipment worn-out

leads to additional conservatism in the estimate of dollar savings in peacetime spares support.

Basic Assumptions

For the purpose of this analysis, spares requirements and spares availability were assumed to be in constant equilibrium. In other words, if a comparison of requirement and availability indicated the need for additional spares for a particular quarter, the needed spares were considered to be immediately available; the cost of this pre-planned purchase was then charged to the associated fleet configuration for the quarter in which the requirement appeared. This assumption further indicates that the repair pipeline is always full and that the peacetime stock level is always adequate for each quarter through advanced planned purchases (Provisioning Conferences and Replenishment Planning). The only reason for increased requirements in succeeding quarters is the increased number of flying hours due to the increase in fleet size. The same need could result from a stable fleet size but an increase in flying activity. Since wearout and condemnation were not considered, should the fleet flying hour rate be held constant there would be no need for additional purchase of spares.

The estimate of potential savings in spares requirements was concentrated in the two areas stressed above, namely, the peacetime stock level and the supply pipeline. The technique used was to compare the requirements for a fleet having the RIP configuration with the requirements for a fleet which does not have the benefit of an intense reliability improvement program.

In the assumed situation, F105D RIP aircraft are delivered to the Air Force starting in January 1964 at a rate of 60 aircraft per quarter, or 240 aircraft per year, for a period of two years. Spares requirements for the RIP fleet are based upon the MTBF estimated by the various suppliers as achieveable by 1964 through the concentrated Reliability Improvement Program.

The non-RIP fleet consists of F105D aircraft, of the present basic configuration, each aircraft containing an integrated electronic system improved only through normal growth (ECP action). The production rate was also 60 per quarter or 240 aircraft per year, for a period of two years. Spares requirements for the "growth" fleet were based upon the MTBF estimated as achieveable through normal growth by 1964. This projected MTBF was extrapolated from a 5 year history of F105D electronic equipment measured MTBF, and system reliability growth potential. In both cases, that is for the "growth" and RIP fleets, it was assumed that

1. the flying hour program is 75 hours per aircraft per quarter and
2. the peacetime attrition rate is 12 aircraft per 100,000 flying hours.

Power-on operating time is the only base for acceptable measure of mean time between failure for electronic equipment. It is assumed that all electronic equipment is in operation during all flights, and that the ratio of ground to flight operating time for all electronic systems is 3:1 (the ratio at the RAC production flight line varies from 6:1 to 15:1 depending upon the particular system in question). The significance of this ratio is that each piece of equipment is operated three hours on the ground for each hour of flight. Computations were then repeated for ratios of 2:1 and 1:1.

All items in base repair were considered to be returned within the quarter, thus requiring no spares to support the base repair pipeline. The depot repair cycle was assumed to be 38 days for all components, resulting in the return of 58% of all depot reparables within the quarter in which the components failed, and 42% returned in the succeeding quarter. Each component was evaluated as to its capability of being repaired at base level through use of the latest applicable High Value Review Board Check Sheet (AMC Form 231) and discussion with Field Service specialists thoroughly familiar with the airborne equipment and Air Force base repair capability. Base repair capability is expressed as a percent of all failures estimated to be reparable at organization or field level.

Estimating Technique

The number of failures per component per

quarter year was determined by dividing the estimated average number of equipment operating hours accumulated by the installed equipment in fleet inventory during the quarter under investigation, by the Mean Time Between Failure of the component in question. The quantity of serviceable components available within the current quarter was determined through application of the base and depot repair capability estimates together with the estimated percent of depot reparables returned within the quarter. The total depot reparables returned consists of 42% of those failed components returned to the depot during the preceeding quarter as well as 58% of those returned to the depot during the current quarter.

The entire analysis is based upon the techniques described in AMCM 400-1 and Spares Study Group Report No. 8 (December 1958) and outlined in AMC Form 326. Only those calculations were used which are involved in determining the peacetime stock level and depot repair pipeline requirements. With this limitation, in addition to the limitations imposed by the basic assumptions previously described, it was possible to eliminate the following computations:

1. WRM replacements. (War Reserve Materiel)
2. FAK requirements (Flyaway Kits)
3. Overhaul support requirements
4. Condemnation and wearout replacements
5. Support of non-recurring requirements
6. Planning of the Material Repair System
7. Planning for Procurement
8. Spares distribution to user bases
9. Retention level planning

Typical Computation

A sample spares requirement computation is shown in Figures 6 and 7 for an Autopilot "Black Box". The computation essentially follows the procedure outlined in AMC Form 326, as previously stated. This single computation, for only one sub-assembly within the autopilot subsystem, indicates the tremendous potential for savings in spares requirements, for a quarterly saving of over $88,000 (25 pcs) is estimated to be realized. The same technique was repeated for all major components of each subsystem to produce the total estimated annual savings of $54,000,000 compared to an estimated Reliability Improvement Program non-recurring cost of some $25,500,000 (Figure 8).

Sensitivity Tests

In computing the savings in spares requirements due to the improvement in reliability of the airborne electronic equipment, several assumptions were made, all of which have been discussed in previous sections of this paper. All of the assumptions are considered to be in the direction resulting in a conservative estimate of savings. Two assumptions which may not appear to be conservative are:

a. that the estimated reliability achievement will in fact, be achieved, and

b. that the ratio of ground operating time to flight time is 3 hours on the ground to each hour of flight.

Since computed savings are affected by these parameters, the computation of savings was repeated to indicate the sensitivity of savings to partial achievement of estimated reliability improvement and to a reduction in equipment total operating time (essentially a reduction in the ratio of ground time to flight time). Figures 8, 9, and 10 include the results of a computation of estimated savings with ground time to flight time operating ratios of 3:1, 2:1, and 1:1; in addition to the effect of achieving 100%, 75%, 50%, and 25% of the estimated improvement in reliability.

The results of this analysis indicate that the Doppler Navigator, Central Air Data Computer and NASARR Radar have the most potential for dollar savings in peacetime spares. In particular, the Doppler system improvement resulted in not only an improvement in reliability but a substantial reduction in estimated price, such that significant savings are realized even if no reliability improvement is achieved.

Proposed improvement of the Vertical Tapes (Integrated Instruments) and All Attitude Platform do not indicate as dramatic a saving as with the systems discussed above. Proposed improvement of the Automatic Flight Control, Communication-Information-Navigation and Toss Bomb Computer/Sight Display systems show extreme sensitivity to partial accomplishment of estimated improvement and reduction in equipment operating hours.

Although large peacetime savings are not indicated for every subsystem, the non-assessed benefits, such as increased aircraft utilization, improved mobility of flyaway kits, increased probability of completing a mission and reduced maintenance requirements, may, in the opinion of the customer, counterbalance comparatively small peacetime savings sufficiently to make the improvement in reliability worthy of the investment required.

MISSION COMPLETION CAPABILITY

One of the primary effects of improving the reliability of the F105D electronic systems is the corresponding increase in mission completion probability. That is, the likelihood that the weapon system will function in such a manner that the mission objective will be achieved. There are two essential mission objectives which must be satisfied; that of the Contractor and that of the using agency.

The Contractor's objective is to deliver the weapon system to the customer with all subsystems fully operational. The Air Force ob-

jective is to successfully complete a combat mission with the weapon system. Consequently the Air Force is concerned with the probability that each sub-system will operate normally for the time required to fulfill its function in the course of the mission. While certain equipment failures can occur without affecting combat mission completion, Air Force acceptance of the weapon system requires that the Contractor demonstrate full operation of all systems prior to delivery. Since the two objectives are apparently incompatible, they shall be considered separately to demonstrate the individual effects of improving system and component reliability.

Republic's time and Failure Reporting Program has produced a wealth of production line reliability data with which to directly compute the probability of production acceptance of the F105D electronic systems. By applying this data to typical combat mission profiles, the probability of mission completion can also be readily computed. The following is a description of the methods used in deriving these two probabilities.

Three stages of system and component reliability, expressed as Mean Time Between Failures, were used as the basis for the analysis. The first stage is the reliability of systems now being produced. The second stage represents the reliability achievable in two years through normal growth, based upon projected system improvements brought about through ECP action, normal component refinement, and advancement on the "learning curve". This is usually accomplished without significant change in basic system design. The third stage is that level proposed by the system sub-contractors for significant system improvement.

Production Acceptance

USAF acceptance of the weapon system from the contractor has been assumed to require that every subsystem of the F105D electronic system operate without failure for a two hour flight. Using the system failure rates described in the foregoing section and the equation of the exponential function,

$$P = e^{-t/T}$$

where:

P = probability of successful completion
e = Naperian Base, 2.7183,
t = equipment operating time = 2 hours,
T = Mean Time Between Failures, hours and
1/T = Failure Rate,

the improvement in probability of an Air Force acceptance pilot experiencing no electronic system failures during a total of two flight hours on one aircraft was found to be a 9% increase in acceptance probability at the end of two years through normal product improvement. If, however, the proposed Reliability Improvement Program is undertaken, an increase of 36% in acceptance probability is achieveable in the same time period.

Mission Completion

The probability of acceptance given in the preceding section is a convenient measure of the total reliability of the F105D integrated electronic systems operating for two hours in flight. However, an indication of weapon system combat effectiveness is the probability of the electronic systems operating properly during the mission for which the weapon system was designed. Representative basic missions of the F105D (2 hours duration) were analyzed for various weather, weapon and delivery modes to determine electronic system mission completion probability. Subsystems included in each mission analysis were limited to those required to accomplish the particular mission under study, each of which were assumed to operate for the full duration of the mission.

The three stages of system reliability and the equation previously described were used in the computation of electronic system mission completion probabilities with the qualification that only system modes were included which were required for the particular mission.

The normal growth improvement in electronic system probability of mission completion is thus estimated to be 6%, while the RIP program would yield a corresponding improvement of 18%. These figures were found to be approximately the same for both the LO-LO-LO-Hi and the HI-LO-LO-HI mission profiles, under blind weather conditions. In clear weather, the MTBF's are higher, but the percent improvement is about the same.

CONCLUSION

Reliability is an investment that returns dollars to the customer in the form of reduced cost of maintenance support and increased efficiency of the weapon system. However, if the investment is delayed so that the result appears late in the operational life of the weapon system, the necessary investment to achieve the same result, will increase. This is due to the necessary reduction in the flexibility of permissable changes as the quantity of existing systems increases and the quantity of future production decreases. In addition, flexibility is further reduced as more Aero Ground Equipment is introduced which requires additional expenditure of funds to make the equipment compatible with modifications to the airborne equipment.

Studies have further indicated that it is extremely difficult, if not impossible, to financially justify retrofit costs, for the cost of retrofit is a direct expenditure that cannot be compared with anything but the cost of not per-

forming retrofit, which is no cost at all. In addition, supporting spares are scheduled to be on hand prior to delivery of the equipment to be maintained. Therefore, if sufficient spares were procured, an improvement in reliability of the basic equipment will create a surplus of supporting spares, rather than a saving in future procurement. The only saving that can be realized in a retrofit program to improve reliability is in the area of reduced manpower requirements, reduced requirement for replacement bits and pieces and, reduced requirement for additional spares (if additional spares must be procured).

In summary, maximum benefit is obtained from early investment in reliability, which will increase first cost, but which must be considered as an investment with a virtually guaranteed return.

FIGURE 1
COST vs RELIABILITY

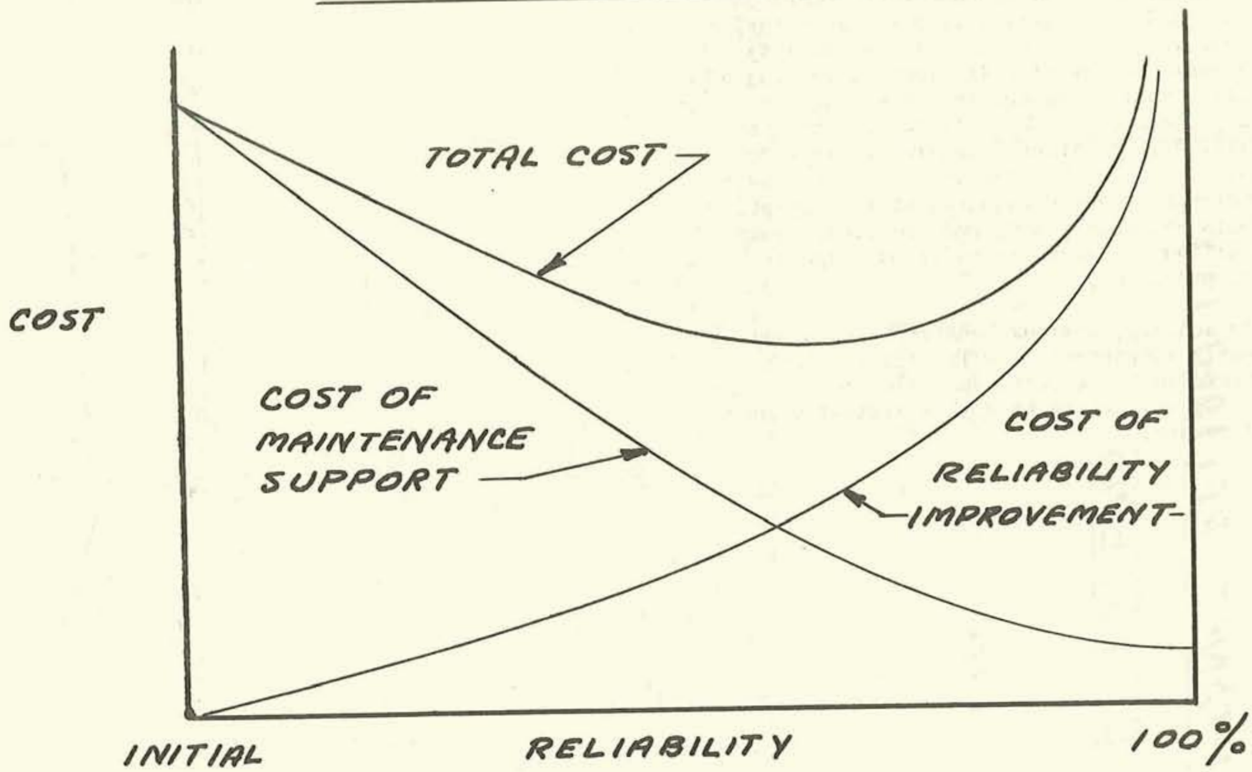


FIGURE 2
SYSTEM MTBF

SYSTEM	JANUARY 1961	PROJECTED 1963	ULTIMATE GOAL	RIP 1963
* AUTOPILOT	90	100	500	190
* DOPPLER	15	20	500	185
* CIN	30	40	500	86
* PLATFORM	175	250	920	518
* V-TAPES	350	500	1130	1050
* CADC	170	200	1600	1050
** FIRE CONTROL	13	16	500	40

* GFE
** CFE

FIGURE 3

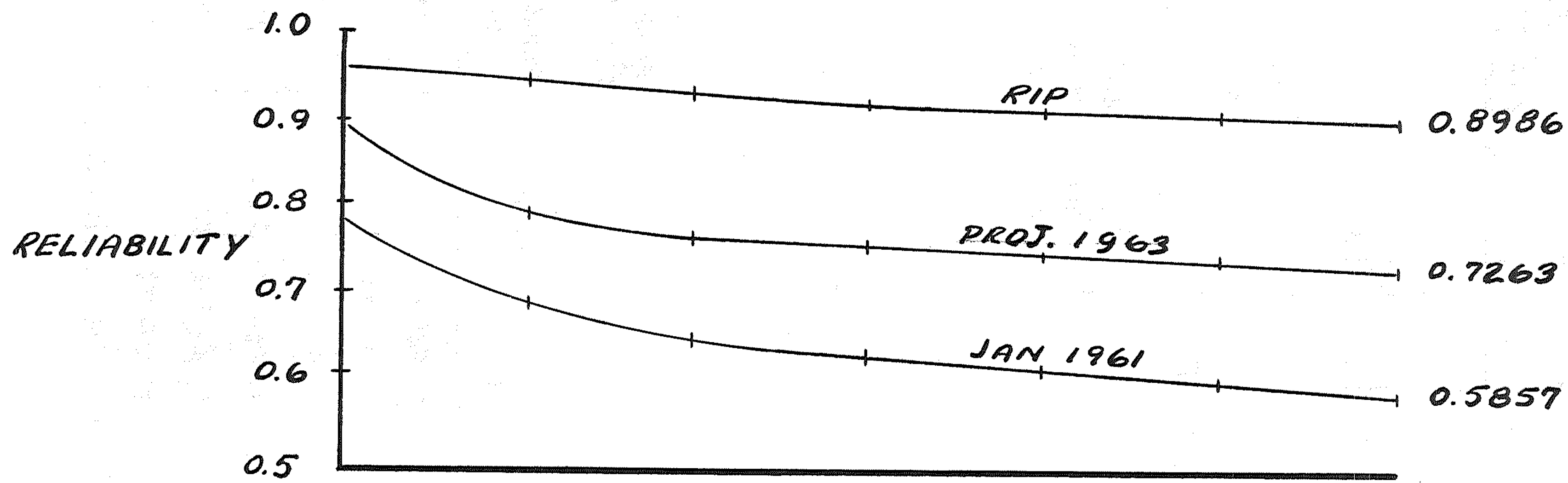
CUMULATIVE ACCEPTANCE RELIABILITY

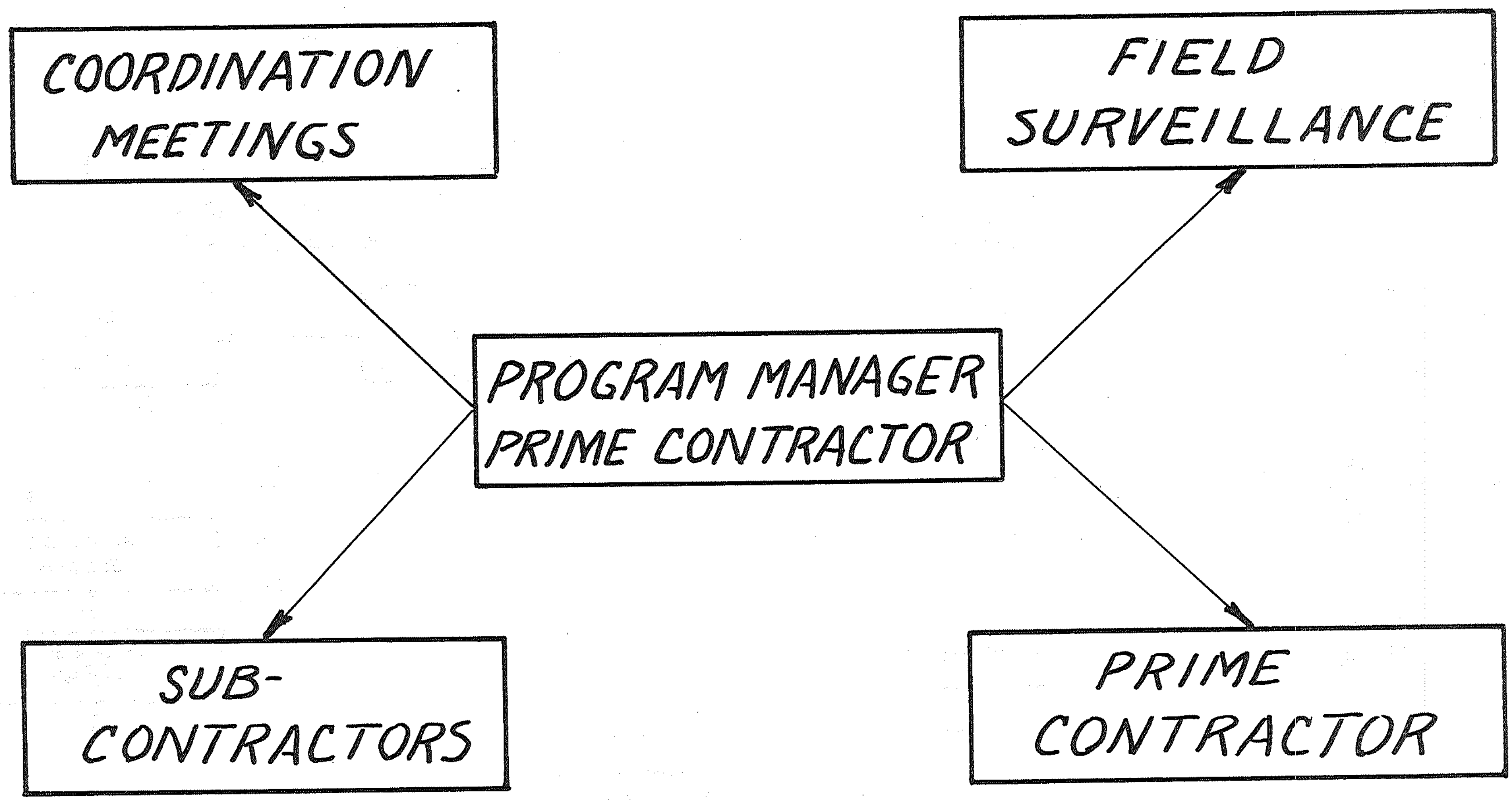
ELECTRONIC SYSTEMS

RELIABILITY $= e^{-t/T}$ WHERE $T =$ MTBF, hrs.

$t = 2$ hrs

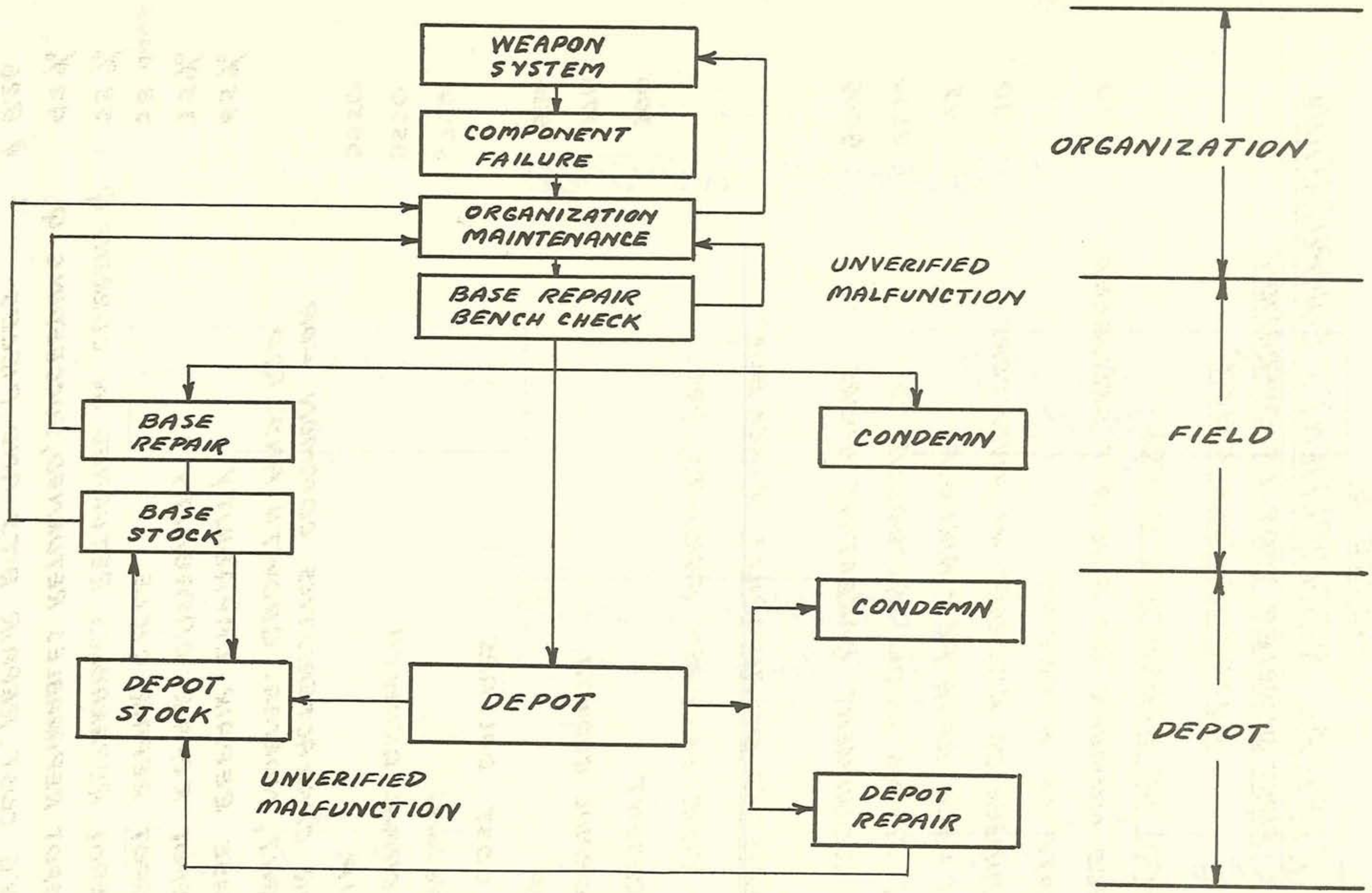
SYSTEM	FIRE CONTROL	DOPPLER	CIN	AFCS	CADC	PLATFORM	V-TAPES
RIP	.9511	.9862	.9775	.9896	.9981	.9937	.9955
PROJ. 1963	.8825	.9048	.9512	.9801	.9900	.9920	.9934
JAN 1961	.7866	.8752	.9407	.9607	.9802	.9802	.9802





PROGRAM MANAGEMENT

FIGURE 4



COMPONENT PARTS FLOW

FIGURE 5

FIGURE 6

TYPICAL REQUIREMENTS COMPUTATION

FIRST QUARTER YEAR OF OPERATION

AUTOPILOT "BLACK BOX"

DERIVATION OF OPERATING HOURS

a. AVERAGE NUMBER OF AIRCRAFT DELIVERED	30
b. ESTIMATE OF ATTRITION	0
c. AV'G NUMBER OF AIRCRAFT IN INVENTORY	30
d. FLYING HOUR RATE PER AIRCRAFT	75
e. TOTAL FLYING HOURS ACCUMULATED	2250
f. TOTAL EQUIPMENT OPERATING HOURS	9000

CHARACTERISTICS OF AUTOPILOT "BLACK BOX"

a. MEAN TIME BETWEEN FAILURES, HRS.	
PRESENT	300
NORMAL GROWTH	376
RIP	986
b. UNIT COST, DOLLARS	
PRESENT	3750
NORMAL GROWTH	3550
RIP	3550
c. REPAIR CHARACTERISTICS COMMON FOR PRESENT, NORMAL GROWTH AND RIP	
BASE REPAIR CAPABILITY	65%
DEPOT REPAIR CAPABILITY	35%
DEPOT REPAIR CYCLE	38 days
DEPOT REPARABLES RETURNED IN CURRENT Q	58%
DEPOT REPARABLES RETURNED, SUCCEEDING Q	42%
AV'G COST, REPAIR BITS AND PIECES	\$ 8.26

FIGURE 7

TYPICAL REQUIREMENTS COMPUTATION

FIRST QUARTER YEAR OF OPERATION
AUTOPILOT "BLACK BOX"

REQUIREMENTS COMPUTATION

ITEM	NORMAL GROWTH	RIP
a. EQUIPMENT OPERATING HOURS	9000	9000
b. OPERATING REPLACEMENTS OR REPAIRS, 9000/MTBF	24	9
c. OPERATING STOCK LEVEL, 1/2 OF REPLACEMENTS FOR SUBSEQUENT QUARTER	36	13
d. BASE REPAIRS, 65% OF b.	16	6
e. DEPOT REPAIRS, 35% OF b.	8	3
f. DEPOT REPARABLES RETURNED CURRENT QUARTER, 58% OF e.	5	2
g. DEPOT REPARABLES RETURNED FROM PREVIOUS QUARTER	0	0
h. TOTAL SERVICEABLE ASSETS, d. + f. + g.	21	8
i. REQUIREMENT SUMMARY		
OPERATING STOCK LEVEL, ITEM c.	36	13
OPERATING REQUIREMENT, ITEM b.-ITEM h.	3	1
j. TOTAL NUMBER OF REPAIRS, CURRENT QUART.	21	8

COMPUTATION OF DOLLAR SAVINGS, FIRST QUARTER

ITEM	NORMAL GROWTH	RIP	SAVING
a. TOTAL SPARES REQUIREMENT	39	14	25 PCS
b. UNIT COST	$3550	$3550	—
c. COST OF SPARES, a x b	$138,450	$49,700	$88,750
d. COST OF UNITS INSTALLED IN AIRCRAFT DELIVERED THIS QUARTER (60 AIRCRAFT)	213,000	213,000	NONE

TOTAL DOLLARS SAVED $88,750

FIGURE 8

ANNUAL SAVINGS VS ACHIEVED PERCENT OF ESTIMATED IMPROVEMENT

RATIO, GROUND:AIR = 3:1

SYSTEM	ESTIMATED IMPROVEMENT (PERCENT OF)				PROGRAM COST PER SYSTEM
	100	75	50	25	
AUTOPILOT	$ 230	$ 150	$ 10	$ (160)	$ 670
DOPPLER	34,540	33,630	31,910	28,050	9,710
CIN	1,360	1,060	700	(20)	930
PLATFORM	480	450	390	340	2,160
V-TAPES	540	510	450	340	325
CADC	3,920	3,790	3,530	2,980	518
FIRE CONTROL	12,920	11,000	8,310	3,750	11,210
TOTALS	$53,990			$35,280	$25,520

NOTE: "000" OMITTED

FIGURE 9

ANNUAL SAVINGS

VS

ACHIEVED PERCENT OF ESTIMATED IMPROVEMENT

RATIO, GROUND:AIR = 2:1

SYSTEM	ESTIMATED IMPROVEMENT (PERCENT OF)				PROGRAM COST PER SYSTEM
	100	75	50	25	
AUTOPILOT	$ 60	$ (10)	$ (110)	$ (240)	$ 670
DOPPLER	26,490	25,810	24,540	21,720	9,710
CIN	840	610	340	(170)	930
PLATFORM	420	390	350	310	2,160
V-TAPES	430	400	365	280	325
CADC	3,150	3,060	2,860	2,450	518
FIRE CONTROL	8,930	7,480	5,490	2,080	11,210
TOTALS	$40,320			$26,430	$25,520

NOTE: "OOO" OMITTED

FIGURE 10

ANNUAL SAVINGS

VS

ACHIEVED PERCENT OF ESTIMATED IMPROVEMENT

RATIO, GROUND: AIR = 1:1

SYSTEM	ESTIMATED IMPROVEMENT (PERCENT OF)				PROGRAM COST PER SYSTEM
	100	75	50	25	
AUTOPILOT	$ (120)	$ (160)	$ (230)	$ (320)	$ 670
DOPPLER	19,320	18,860	17,990	16,060	9,710
CIN	320	170	(10)	(350)	930
PLATFORM	350	340	310	280	2,160
V-TAPES	330	320	290	230	325
CADC	2,390	2,330	2,200	1,920	518
FIRE CONTROL	4,940	3,680	2,490	340	11,210
TOTALS	$ 27,530			$ 18,160	$ 25,520

NOTE: "000" OMITTED

RELIABILITY MONITORING BY OPTIONAL STOPPING SAMPLING

Norman R. Garner
Aerojet-General Corporation
Azusa, California

17299

Abstract

An optional stopping sampling procedure is recommended for reliability monitoring. This procedure allows testing to continue until k defects are observed. At this time one of three decisions are made. If the number of trials is too small, testing is stopped and an engineering change is required. If the number of trials is too large, then a new reliability plateau has been achieved. If the number of runs is neither too small nor too large a new sequence of testing begins. Thus, only a minimum amount of testing would be performed on unreliable systems - a very desirable characteristic for the proper monitoring of reliability. On the other hand, if an engineering design change was made which improved reliability appreciably, the length of trials would become longer and, so, a more efficient estimate of reliability would be made for the improved system. This is precisely what is desired by a monitoring system. The mathematical model is discussed, cumulative probabilities are given so that control charts can be established, and, finally, an example is presented.

Reliability Monitoring Requirements

Every development program can be considered as an evolutionary process; a process which requires a continuous series of engineering changes. As these changes are made, it is desirable to continuously monitor the development program to determine which engineering changes are beneficial and which are detrimental. It is essential, therefore, that a monitoring procedure be developed which allows rejection of an engineering change as soon as possible if it is detrimental but allows testing to continue if it is beneficial. This is consistent with the ideas of (1) minimum cost since it will minimize testing, (2) eliminating causes of non-improvement, and (3) obtaining test results which convey most efficiently the current estimate of reliability.

In essence, at least a three decision process is required. One decision says stop testing, reliability has decreased and no more testing should be performed until an engineering change is made. A second decision says that the engineering changes have increased reliability and, so, a new reliability plateau has been achieved. A third decision is, of course, continue testing, insufficient evidence to determine (1) or (2). A sampling procedure, commonly called optional stopping or inverse sampling, can fulfill all of these requirements.

Optional Stopping Sampling Procedure

The optional stopping sampling procedure tabulates the number of trials up to and including k failures, where k is a preassigned number of allowable defects. Thus, as the success runs or number of trials become larger, it would be assumed that the reliability has improved; as the success runs become smaller, it would be assumed that the reliability has degraded. So, it is possible to control developmental decisions by observing the length of runs; that is, the number of trials required up to and including k failures. For example, if an engineering change caused a degradation in reliability, or if wearout were becoming an important reliability variable, the observed lengths of trials would decrease significantly. This would call for a stopping of testing until an engineering change were made. Thus, only a minimum amount of testing would be performed on unreliable systems - a very desirable characteristic for the proper monitoring of reliability. On the other hand, if an enginee[illegible] design was made which improved the reliability appreciably, the lengths of trials would become longer and, so, a more efficient estimate of reliability would be made for the improved system. This is precisely what is desired by a monitoring system. This procedure is in effect continuous surveillance on the development program and when k defectives are observed a decision is to be made. It is, of course, a form of sequential sampling. That is, in contrast to fixed sampling programs, the sample size, n, is a random variable.

Mathematical Model for the Optional Stopping Sampling Procedure

The mathematical model for this procedure is given in Feller as

$$P(X=n) = \binom{n-1}{k-1} (1-R)^k R^{n-k} \qquad n=k, k+1, \ldots$$

where $P(X=n)$ is the probability of a run of n trials up to and including the kth failure (the number of failures allowed before sampling is stopped); and R is the current reliability of the system. This model is known as the Pascal or, more popularly, the negative binomial distribution.

Feller also shows that the mean or expected number of trials up to and including the kth defect is

$$E(X) = \frac{k}{1-R}$$

and its variance is

$$\sigma^2(X) = \frac{kR}{(1-R)^2}$$

If k is preassigned as unity then Pascal's distribution reduces to the well known geometric distribution

$$P(X=n) = (1-R)\,R^{n-1} \qquad n \geq 1$$

with the expected number of trials up to and including the first defect

$$E(X) = \frac{1}{1-R}$$

and its variance

$$\sigma^2(X) = \frac{R}{(1-R)^2}$$

When it becomes necessary to estimate R from a series of trials when k has been assigned, Haldane has shown that an unbiased estimate of R is

$$\hat{R} = \frac{n-k}{n-1}$$

and Finney has shown that an unbiased estimate of its variance is

$$s^2_{\hat{R}} = \frac{\hat{R}(1-\hat{R})}{n-2}$$

Finney recognized that the standard error is a satisfactory estimate of the error of estimation of R only when k is large and states that for small k limits of error can be computed from binomial tables by the following rules:

1. The lower limit is one minus the upper limit for a direct binomial sample which has k-1 failures in n-1 trials.

2. The upper limit is one minus the lower limit for a direct binomial sample which has k failures in n trials.

These limits are the highest and lowest values of R which just fail to be contradicted by the sample in a significance test based upon a chosen level of the probability.

Establishing the Control Chart

The cumulative probabilities have been summarized for k=10 and for reliabilities of .85 (1) .99 for control chart limits in Table I. The median value is also given. In the body of the table are the allowed number of tests up to and including the kth failure before a decision is to be made. For example, with k=10 and an assumed reliability of .90, if 56 or less tests were observed up to and including the 10th failure, testing would stop and would not continue until an engineering change were made. On the other hand, if 154 or more tests were observed, it would be decided that a new plateau or a new reliability had been obtained. A new estimate of reliability would be assumed and new limits determined. Otherwise, a new series of tests is commenced. These limits are chosen with a 5% error of making a false change in the current reliability status.

A question which arises is the level of control required. Conventional control charts customarily use the 95% (2σ) or 99.7% (3σ) limits. However, optional stopping sampling charts are for detecting changes of two independent events to provide a basis for independent decisions. For example, if a point goes out on the low side no revision is made to the limits, but a change is made to the process. In other words, these charts are for the purpose of detecting changes in reliability on a product which is continually altered by engineering changes, not to maintain the product in stable control or its normal pattern of variation. This is perhaps the difference between control charts for developmental work contrasted with mass production. Therefore, it is recommended that the 90% control limits be used. That is, 5% for each side, or each decision.

When it is decided that a new plateau has been achieved, a problem arises in determining the new reliability; however, it is suggested that only points on the upturn be used to determine this value for control limits. This value, of course, could be adjusted as evidence is accumulated. These charts should be studied just as regular control charts. For example, they should be watched for significant gaps, trends, or runs above or below the median value. A skilled statistician should be available for consultation.

The choice of k is more or less arbitrary. One should choose k according to a desirable operating characteristic curve, financial availability, or both. If the reliability is assumed to be rather low perhaps values of k=4 to 10 could be used. However, as the reliabilities get higher and higher, the only choice is to let k=1 or 2.

Example

A control chart for the 762 consecutive development tests on an Auxiliary Power Supply is shown on Figure 1 for k=10. The results are also presented in Table II. The initial reliability was assumed to be .85 and so, from Table I the lower control limit is 38 tests, the median number of tests is 64, and the upper control limit is 102 tests. On the fifth sequence of 10 failures, a run of 134 tests was observed which is out of control for a reliability of .85. It is therefore decided that a new reliability is to be assumed and revised control limits determined. Since there is only one point on the upturn the new estimate of reliability is

$$\frac{n-1}{n-1} = \frac{124}{133} = .932 \approx .93$$

Therefore, .93 is the assumed current reliability and the limits are revised accordingly. Obviously these control limits do not take into considera-

tion the sampling variation of the new estimate of reliability. This, however, is of minor importance.

The procedure recommended for the best estimate of current reliability is by grand lotting all data applicable to the current control chart and using the ordinary binomial reliability. Thus, the best estimate of current reliability is

$$\frac{(134 + 129 + 93 + 109) - 36}{(134 + 129 + 93 + 109)} = \frac{429}{} = .923 \quad .$$

References

1. Feller, William, An Introduction to Probability Theory and Its Application, John Wiley and Sons, New York, 1954

2. Finney, D. J., "On a Method of Estimating Frequencies", Biometrika, 36 (1949), pp 233-234

3. Haldane, J. B. S., "On a Method of Estimating Frequencies", Biometrika, 33 (1943-1946), pp 222-224

FIGURE 1

OPTIONAL STOPPING SAMPLING CONTROL CHART
FOR THE APS DEVELOPMENTAL PROGRAM

(k = 10, PROBABILITY OF FALSE CHANGE, 5%)

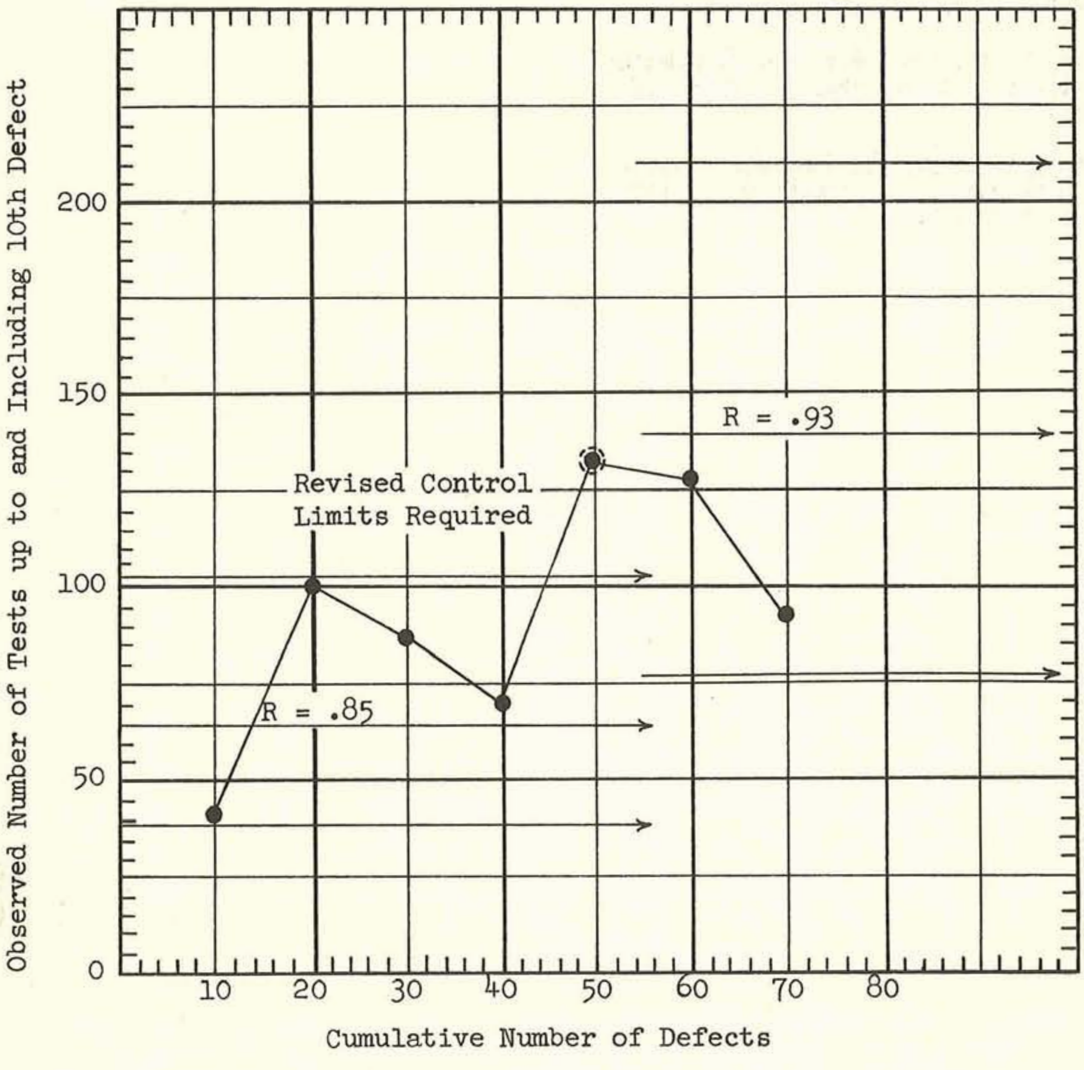


TABLE I

NUMBER OF TESTS AND ASSOCIATED CUMULATIVE PROBABILITIES
FOR k = 10 AND SPECIFIED RELIABILITIES

Population Reliability (%)	Cumulative Probabilities .005	.01	.025	.05	.5	.95	.975	.99	.995
85	28	30	34	38	64	101	110	121	128
86	29	33	36	41	69	109	118	130	137
87	31	34	39	44	74	117	127	140	148
88	34	37	42	47	80	128	139	152	161
89	37	40	46	51	88	139	151	166	176
90	40	44	50	56	96	154	167	183	195
91	44	49	55	62	107	171	186	204	217
92	49	55	62	70	121	193	210	230	244
93	56	62	71	79	138	221	240	264	280
94	65	72	82	92	161	258	281	309	328
95	77	86	98	110	193	311	338	371	394
96	96	106	122	137	241	389	423	465	494
97	126	141	162	183	322	520	565	622	661
98	189	209	242	273	483	782	850	935	994
99	374	416	482	544	967	1567	1704	1873	1994

TABLE II

RESULTS OF 762 DEVELOPMENT TESTS
FOR AN AUXILIARY POWER SUPPLY SYSTEM
$k = 10$

Group	Number of Tests	Number of Failures
1	41	10
2	100	10
3	87	10
4	69	10
5	134	10
6	129	10
7	93	10
8	109	6

STATISTICAL CIRCUIT ANALYSIS IN PRACTICE

F. A. Applegate - N. A. Scianna
Light Military Electronics Department
General Electric Company
Utica, New York

17300

Abstract

In recent years several methods of relating component part behavior to circuit behavior have been described; however, the author knows of no papers relating the so-called statistical circuit analysis to a component-part test program.

Assuming a correct model, circuit synthesis is only as good as the component part data used. Because of this dependence upon accurate component part data, considerable effort must be expended in designing an accurate and efficient component-part testing program. The results of this test program must lend themselves to any analysis model selected.

This paper, then, describes a program for the collection and use of component-part test data for reliability in general and for statistical circuit analysis in particular.

Introduction

One of the long-standing problems in reliability has been the selection of the component part of highest reliability for a given application. The solution of this problem has followed a somewhat lengthy evolution. From the early simple qualification tests we have progressed to a stage where we now test for the specific reliability of each part and vendor with the most reliable one selected for the application.

Needless to say, all of these methods for selecting parts and vendors are extremely expensive. Besides the expense, it is necessary to keep large samples on test for long periods of time to demonstrate high reliabilities.

The part and circuit standardization of digital equipment persuaded many companies to test a few parts and circuits intensively. These same companies soon realized, however, that it was extremely wasteful to test just for the sake of reliability numbers, and they began to measure some of the more important part parameters. Unfortunately, most companies, vendor and user alike, continue to test at maximum operating conditions only. Some--in hopes of achieving an accelerated test--operate the part in excess of rating. In any event, component-part parameter data in distribution form have now became available.

With this data in existence for various temperature, electrical, and environmental conditions, it was natural to start designing circuits which would operate at the worst case combinations.

Several objections were found to this "worst case" design. In some cases, a worst case design could not be found. In others worst case design was found to be unduly pessimistic. Some worst case combinations just could not exist, and even the very definition of what constituted a worst case value was questionable.

Most of the difficulties can be overcome, however, and useful worst case circuits can be designed. These designs can be improved by considering the statistical implications of the worst case limits. In other words, the approach to design is changed to tolerate specific areas of part parameter distributions.

With a statistical circuit analysis, it is readily apparent if a design requires improvement. In fact if the analysis is made properly, it can even reveal the specific part parameters that need to be improved.

General Plan

Because the general reliability program which follows is dependent upon the degree of part and circuit standardization realized, the first reliability objective is to meet the required standardization. Experience has shown that this must be accomplished in the proposal phase if standardization is to become a reality.

Today's digital equipment permits extensive use of standard parts and circuits, but what of those equipments which will not permit such standardization? The same general reliability program can be applied, but it will be extremely expensive if followed to the extent described here. The approach described is for digital equipment; for other designs the program will usually have to be far less extensive.

Initial circuit design can be accomplished by using worst case values which are either calculated from prior data or obtained from vendor data. This is done to achieve a working design as early as possible so that other design work may proceed. In actuality, many of the circuit designs based upon the design procedures described here will already exist from prior development.

Following the initial design a detailed circuit analysis is started on all new circuit designs. This analysis is begun at the same time as the parts testing program. The purpose of the circuit analysis is to derive an expression in terms of measurable part parameters for each circuit parameter. The fact that measurable part parameters must be used in the derived expression eliminates many possible expressions. This is the major problem in finding ac-circuit expressions

Considerable effort must be expended to make the part-testing program efficient for this activity is the most expensive portion of a reliability program. The circuit synthesis which follows the part-test program is only as accurate as the component-part data used. Accuracy, therefore, is a continual concern in part testing. The results of the test program must be put into a form so that any circuit synthesis method may be used. The data must also permit determination of worst case values. Simultaneously with the generation of part parameter data, vendors are ranked for quality, and actio is initiated to correct for any component part deficiencies.

Following the generation of component part parameter distributions, this data is combined with the circuit parameter expression derived from the circuit analysis. Several methods exist for this procedure, the most common of which is the "Monte-Carlo" or random-sampling technique. The result of any of these procedures is a distribution of the circuit parameter according to the individual component-part parameter variations.

Using the circuit parameter distribution along with some criteria of satisfactory circuit parameter performance, it is possible to determine which designs are satisfactory and which are not. Design improvements can then be initiated where the need exists.

Part Test Program

Although the part test program functions as a tool for vendor selection as well as the source of part parameter design data, this discussion will be limited to the testing program for a single vendor. Other vendors require essentially a duplication of the described effort.

Before subjecting a part to an extensive test program, it is first ascertained that the part does exhibit the electrical characteristics desired. This is determined through a series of measurements on separate samples from those later subjected to reliability testing.

Sample sizes are determined to provide statistically valid results from all testing. To minimize sample sizes prior information including vendor data is used whenever it is available. No fixed sample size is correct for all tests, but the size usually varies between 25 and 300 with 50 being the most common. It is significant that failure rates are not a product of this testing, but detailed parameter data. This accounts for the relatively small sample sizes.

The part test program is designed to investigate many different considerations, from environmental to electrical. No test program can be the final answer in test techniques. The procedures are continually being improved upon as new methods are found to conduct more accurate tests, more economically. The only fixed requirement is to obtain data describing the variation of the part parameter under environmental and electrical conditions, and over the intended operational life.

Usually a vendor's samples are divided into at least three groups. One sample is subjected sequentially to each of the environmental conditions to be encountered in operation. The order of sequencing is normally selected at random except where several vendors are being compared, in which case identical order is followed. The second sample is placed directly on an operating life test. The third sample is subjected to an environmental exposure which is suspected of being detrimental to the part. This sample is then placed on an operating life test identical to the second sample.

The life tests can be either a steady state test, an on-off cycled test, a temperature-cycled test or both. The type depends upon the intended operational use of the equipment. The fact that life tests are conducted under actual electrical conditions expected in operation is a significant departure from most part testing and is desirable for two reasons: (1) Semiconductors can be less stable at low levels of operation than they are at rated conditions (2) We are looking for accurate answers in the circuit synthesis described in this paper, and therefore, we want to minimize errors introduced into the calculations. The life test is conducted (if non-cycled) at the maximum expected operating temperature, but measurements are taken at room temperature and low temperature as well.

In addition to the testing described, data is gathered so as to construct families of curves wherever vendor data does not furnish adequate results. These families of curves include electrical and temperature variations.

By data reduction we attempt to provide maximum information in s implest form. The data is directed at two groups of people. Curves with brief

tables of worst case values are constructed for design engineers. Additional tables providing the statistics used in reliability circuit analysis are constructed for reliability engineers.

An example of curves prepared for designers is the transistor curves in Figure 1. Figure 2 is a specific transistor parameter showing the mean and a measure of dispersion. Figure 3 presents the results of a typical life test with the 25°C measurements.

Figure 4 is another plot of the same data shown in Figure 3. But this time it is intended for reliability engineers. Another version of this plot, which is used for quick communication of sample distribution changes, uses the sample item number to check individual items.

Table 1 presents the sample statistics recorded from a typical test. These tables which are retained by Reliability Engineering are intended to provide the statistics which might be required by any group. Definitions are shown in Appendix A. A similar table represents percent changes.

Each table and graph records specific vendor and part type except for those cases where collective data represent a part type made by several vendors. Besides the tables and graphs retained by reliability, the raw data is kept until the part type is obsolete.

Another table provided designers for use with a specific design is a table of worst case limits. These limits are specific for each design because of varying temperature, life, and environmental requirements. Table 2 is a brief example of such a table.

In addition to the data reduction already described, various analysis techniques are used in forming inferences about the populations. Regression analysis is performed wherever called for, and often special correlation studies are made for use in the statistical circuit analysis described below. Various tests of hypotheses are made in selecting vendors, evaluating part improvement, and so on. Generally, besides being scrutinized for the specific purpose of the test, the data is carefully analyzed for whatever other information it might yield.

Statistical Circuit Analysis

The first step in performing a statistical circuit analysis or a worst case analysis, is to find an expression for each circuit characteristic in terms of measurable part parameters. A criterion must also be established for the unsatisfactory performance of each circuit characteristic.

As an example of the derivation of circuit equations used in worst case and in statistical circuit analysis, the dc equations for what has been called a "standard" Nor circuit will be derived. This circuit is shown in Figure 5. Such derivations must be accomplished for each circuit parameter of every circuit used.

Examination of the Logic Nor shown in Figure 5 reveals two modes of failure. These modes can be expressed as circuit parameters, and their equations can be derived.

Failure Modes

The first mode of failure is the circuit's inability to deliver the specified amount of load current. This Nor was designed to deliver four units of such current. Degree of overdrive (DOD), which is used as a figure of merit, is set equal to the product of the transistor current gain and the base current of the transistor, divided by the maximum required output current (four units of load current). This is expressed as:

$$DOD = \frac{h_{FE} I_B}{4 I_L}$$

where: h_{FE} is the transistor current gain
I_B is the transistor base current
I_L is one unit of load current

Failure occurs when DOD is less than one.

The second mode of failure in this Logic Nor is for the circuit to be conducting when cutoff is desired. The Nor transistors must not conduct when one of the input diodes is forward biased and returned to ground through a saturated transistor. Failure occurs when the base to emitter voltage of the transistor (V_{BR}) reaches a critical value that permits conduction.

For definition of symbols used in the following derivations see Appendix B.

Derivation of Transistor Base Current (I_B)

Referring to Figure 6A, assume that Q1 is conducting. Let I_l represent the total leakage at the input of the circuit.

$$(1)\ I_1 = I_2 + I_l$$

$$(2)\ I_2 = I_3 + I_B$$

$$(3)\ E_1 + E_2 = I_1R_1 + I_2R_2 + I_3R_3$$

$$(4)\ I_3 = \frac{E_2 + V_B}{R_3}$$

where V_B is the transistor base to emitter voltage at saturation. For I_1 in equation (3), substitute equation (1).

$$(5)\ E_1 + E_2 = I_lR_1 + I_2(R_1+R_2) + I_3R_3$$

For I_2 in equation (5), substitute equation (2).

$$(6)\ E_1 + E_2 = I_1R_1 + I_3(R_1+R_2+R_3) + I_B(R_1+R_2)$$

For I_3 in equation (6), substitute equation (4).

$$(7)\ E_1 + E_2 = I_1R_1 + \frac{(E_2+V_B)(R_1+R_2+R_3)}{R_3} + I_B(R_1+R_2)$$

After simplifying and solving for I_B

$$(8)\ I_B = \frac{E_1}{R_1+R_2} - \frac{E_2}{R_3} - \frac{I_1R_1}{R_1+R_2} - \frac{V_B(R_1+R_2+R_3)}{R_3(R_1+R_2)}$$

Derivation of One Unit of Load Current (I_L)

In Figure 6B one unit of load is the current load one Nor circuit represents. This diagram must be thought of as a load circuit with Q2 being the transistor of the original Nor circuit being analyzed.

$$(1)\ E_1 + E_2 = R_1'I_1 + R_2'I_2 + R_3'I_3 \ *$$

$$(2)\ I_1 = I_L + I_2$$

$$(3)\ I_1 = \frac{E_1 - (V_C+V_D')}{R_1'}$$

$$(4)\ I_3 = I_2 + I_{CER}'$$

For I_1 and I_3 in equation (1) substitute equations (3) and (4) respectively.

$$(5)\ E_1 + E_2 = E_1 - (V_C'+V_D') + (R_2'+R_3')I_2 + R_3'I_{CER}'$$

$$(6)\ I_2 = \frac{E_2 + V_C' + V_D' - R_3'I_{CER}'}{R_2' + R_3'}$$

$$(7)\ I_L = I_1 - I_2$$

$$(8)\ I_L = \frac{E_1 - (V_C+V_D')}{R_1'} - \frac{E_2 + V_C' + V_D' - R_3'I_{CER}'}{R_2' + R_3'}$$

$$(9)\ I_L = \frac{E_1}{R_1'} - \frac{E_2}{R_2'+R_3'} - \frac{(V_C+V_D')(R_1'+R_2'+R_3')}{R_1'(R_2'+R_3')} + \frac{R_3'I_{CER}'}{R_2'+R_3'}$$

*Note: Single primes are used to distinguish parameters appearing in the load from their counterparts in the circuit being analyzed.

Derivation of Degree of Overdrive (DOD)

By definition:

$$(1)\ DOD = \frac{h_{FE}I_B}{4I_L}$$

I_B and I_L were derived above. After proper arrangement of primes in the equation for I_L, these two equations are substituted into (1) for I_B and I_L respectively. The result after simplification is the following expression for DOD.

$$(2)\ DOD = \frac{A}{B}$$

where, $A = h_{FE}R_1'(R_2'+R_3')\left[E_1R_3 - E_2(R_1+R_2) - V_B(R_1+R_2+R_3) - R_1R_3I_1\right]$

and, $B = 4R_3(R_1+R_2)\left[E_1(R_2'+R_3') - E_2R_1' - (V_C+V_D')(R_1'+R_2'+R_3') + R_1'R_3'I_{CER}'\right]$

Derivation of Transistor Base Voltage at Cutoff (V_{BR})

Refer again to Figure 6B. This time it is the circuit instead of the load which is of interest in the derivation.

$$(1)\ E_1 + E_2 = R_1I_1 + R_2I_2 + R_3I_3$$

$$(2)\ I_3 = I_2 + I_{CER}$$

$$(3)\ I_2 = I_1 + I_{CER}$$

$$(4)\ I_1R_1 = E_1 - (V_C''+V_D) \ *$$

$$(5)\ I_1 = \frac{E_1 - (V_C''+V_D)}{R_1}$$

$$(6)\ V_{BR} = R_3I_3 - E_2$$

For I_2 and I_1 in equation (1) substitute (3) and (5) respectively.

$$(7)\ E_1 + E_2 = E_1 - V_C'' - V_D + (R_2+R_3)I_3 - R_2I_{CER}$$

$$(8)\ I_3 = \frac{E_2 + V_C'' + V_D + R_2I_{CER}}{R_2 + R_3}$$

For I_3 in equation (6) substitute equation (8).

$$(9)\ V_{BR} = -(E_2) + \frac{(E_2+V_C''+V_D+R_2I_{CER})R_3}{R_2 + R_3}$$

*Note: Double primes are used to distinguish parameters appearing in the source from their counterparts in the circuit being analyzed.

$$(10)\ V_{BR} = \frac{R_3(V_C''+V_D+R_2I_{CER}) - E_2R_2}{R_2 + R_3}$$

Before the derived circuit expressions are accepted as satisfactory, they should be checked by laboratory measurement of parts and circuits. It is usually a simple matter to insure no gross errors, and quite often approximations are sufficient.

The first step in reliability circuit analysis is to perform a worst case analysis. In this analysis worst case limits, as derived in the part testing program, are entered into the circuit expression, and a determination of circuit acceptability is made. If the circuit works under worst case conditions, the analysis is complete. If the circuit does not work under worst case conditions, then further analysis is required to determine the probability of failure. Table 3 presents the results of a typical worst case analysis on the circuit described above. It can be seen that both circuit parameters fail under worst case conditions.

It can also be seen readily that the worst case conditions cannot arise together. For example low β (h_{FE}) occurs at low temperature while high I_{co} and I_i occur at high temperature. Such inconsistencies can sometimes be resolved by performing the analysis once at high temperature and once at low temperature. If this correction shows that the circuit charac teristic is satisfactory, the analysis can stop. Otherwise, it continues as a statistical circuit analysis.

There are two principal methods of statistical circuit analysis. The first, and most widely used is the Monte Carlo or random sampling technique.[2] This technique randomly samples from the distribution of each part parameter and solves the circuit parameter expression. Many solutions of this expression provide a distribution of the circuit characteristic considered. From this distribution, statistics describing the population can be calculated and used to determine probabilities of failure. This is quite a simple procedure and is relatively quick on high speed computing devices.

The other principal method of statistical circuit analysis is the method-of-moments or the propagation-of-errors technique. Essentially, this technique substitutes a Taylor expansion for the characteristic expression. The theory of propagation of errors permits a combination of component parameter moments to form corresponding circuit characteristic moments. This extremely flexible technique allows for a simple solution of correlated and non-normal part parameters as well as the less complex problems.[1] It has been shown that the two methods provide approximately equal answers. Reference 1 neglects the fact that the method of moments can be made even more accurate by considering correlations and, if necessary a second order expansion.

Using the method of moments, which is well described in references 4 and 5, the following probability of failure from component part variation was found for the circuit example used above:

	DOD	V_{BR}	TOTAL
Standard Nor	.000153	.001395	.001548

Either of these techniques may be performed separately at high or low temperature, at initial conditions, or end-of-life. The usual technique is to synthesize one distribution for all conditions. Although the example deals with transistorized digital circuitry the technique is applicable to tube and analog circuitry. Several of the references deal with such examples.

Conclusions

This program of part testing coupled with statistical circuit analysis has been extremely successful at LMED. Using these techniques along with other elements of a strong reliability program, average component part failure rates of $.008 \times 10^{-6}$ per hour have been achieved. This accomplishment has been achieved with standard production components without benefit of special processing or "burn-in".

With the program in use on several R&D projects, the procedures are continually being improved. For example, studies are now underway to reduce the number of samples tested. It is hoped that one sample can be sequentially subjected to all test conditions, providing greater accuracy at lower cost.

Use of reliability programs like this one actually permit improvements in design reliability. permit the selection of "most" reliable designs and the detection of designs needing improvement. This is a big step toward more reliable equipment.

References

1. Nussbaum, E., Irland, E. A., Young, C. E., "Statistical Analysis of Logic Circuit Performance in Digital Systems", Proceedings of the IRE, Vol. 49 #1, January 1961

2. Hellerman, L., Racite, M. P., "Reliability Techniques for Electronic Circuit Design", IRE Transactions on Reliability and Quality Control, #RQC-14, September 1958

3. Marini, J., Williams, R. T., "The Evaluation and Prediction of Circuit Performance by Statistical Techniques", Proceedings of Joint Military-Industry Symposium on Guided Missile Reliability 1957

4. Hindricks, R. H., "A Statistical Method for Analyzing the Performance Variation of Electronic Circuits", Convair Report No. ZX-7-009, 3 October 1953

5. Hindricks, R. H., "A Second Statistical Method for Analyzing the Performance Variation of Electronic Circuits", Convair Report No. AZ-7-010, 15 February 1956

LME TEST No. 209 Group IA

Evaluation of : 2N697
hFE1 @ +25°C VCE .2V IC 5 ma

N Number is Varying Readings in ______

Time	Initial	280 Hrs.	485 Hrs.	1002 Hrs.	2060 Hrs.	3007 Hrs.	4011 Hrs.	5012 Hrs.	
N	50	49	49	49	48	47	47	47	
$\bar{X}$	44.25180	49.06612	47.45938	50.77163	50.87979	50.90830	52.90744	51.61191	
S^2	46.61542	62.44917	101.18020	93.52771	95.11485	91.06951	105.3586	96.81408	
S	6.82754	7.90247	10.05883	9.67097	9.75268	9.54303	10.26443	9.83941	
Range	34.72000	36.22000	61.20000	41.30000	41.37000	38.03000	41.24000	43.03000	
Min.	34.72000	35.21000	34.25000	34.4500	34.50000	37.62000	38.88000	34.48000	
Max.	69.44000	71.43000	95.45000	75.75000	75.87000	75.65000	80.12000	77.51000	
V	15.42886	15.94058	20.97723	19.04798	18.96737	18.74553	19.40073	19.06423	
S_ϵ	.96556	1.12892	1.43697	1.38156	1.40767	1.39199	1.49722	1.43522	
α_3	1.28208	-4.15079	.29960	1.04021	05.20003	1.11414	1.25447	.98359	
β_1	1.64374	17.22912	.08976	1.08203	27.04037	1.24130	1.57371	.96746	
β_2	5.08306	36.04815	22.90482	3.61693	36.53911	3.62664	4.04626	3.47016	
μ_3	408.0482	-1986.0465	295.63721	940.8748	-4673.7320	968.2764	1356.651	936.9710	
μ_4	11045.47	134904.59	225013.37	31638.86	316933.37	30078.13	44915.32	32525.74	

PERCENTILES

%	Initial		280 Hrs.		485 Hrs.		1002 Hrs.		2060 Hrs.		3007 Hrs.		4011 Hrs.		5012 Hrs.			
	Value	N	Value	N	Value	N	Value	N	Value	N	Value	N	Value	N	Value	N	Value	N
0.5	34.72	1	35.21	1	34.25	1	34.45	1	34.50	1	37.62	1	38.88	1	34.48	1		
1.0	34.72	1	35.21	1	34.25	1	34.45	1	34.50	1	37.62	1	38.88	1	34.48	1		
2.5	34.72	1	35.21	1	34.25	1	34.45	1	34.50	1	37.62	1	38.88	1	34.48	1		
5.0	34.72	2	37.31	2	36.76	2	37.90	2	37.62	2	38.19	2	40.00	2	38.49	2		
10.0	36.76	5	40.32	4	37.88	4	40.29	5	39.71	4	41.01	5	42.30	5	40.71	5		
20.0	39.06	10	42.37	9	39.68	9	42.69	10	42.40	9	42.73	9	44.16	9	43.51	9		
30.0	40.32	15	44.64	14	43.10	14	45.49	15	45.49	14	46.33	14	48.97	14	46.33	14		
40.0	40.32	20	46.30	19	43.86	19	47.66	20	47.66	19	47.66	19	49.85	19	49.01	19		
50.0	42.37	25	47.17	24	44.64	24	49.06	24	48.59	24	49.06	23	50.65	23	49.65	23		
60.0	44.64	30	49.02	29	46.30	29	49.65	29	50.05	28	50.50	28	52.57	28	50.55	28		
70.0	46.30	35	51.02	34	48.54	34	52.46	34	52.13	33	52.13	33	53.82	33	53.07	33		
80.0	48.08	40	53.19	39	51.02	39	54.40	39	55.00	38	55.00	38	56.49	38	56.30	38		
90.0	52.08	45	60.98	44	58.14	44	66.75	44	67.65	43	66.75	42	69.35	42	69.15	42		
95.0	55.56	47	65.79	46	64.10	46	73.52	47	71.53	45	72.56	45	77.76	45	73.63	45		
97.5	58.14	49	65.79	47	64.10	47	75.30	48	72.56	46	74.73	46	79.87	46	74.73	46		
99.0	58.14	49	67.57	48	65.79	48	75.75	49	74.73	47	75.65	47	80.12	47	77.51	47		
99.5	69.44	50	67.57	48	65.79	48	75.75	49	74.73	47	75.65	47	80.12	47	77.51	47		
100.0																		

TABLE 2

WORST CASE DESIGN LIMITS

XYZ Program

Vendor A	1/8 watt resistor	Dwg. No.	Resistance +1.75%, -2.25%
Vendor B	1/8 watt resistor	Dwg. No.	Resistance +1.55%, -2.30%
Vendor C	1 watt resistor	Dwg. No.	Resistance +16.58%, -21.20%
Vendor D	1000 μμfd. 10% capacitor	Dwg. No.	Capacitance +12.20%, -11.60%
Vendor E	Signal Diode	Dwg. No.	V_F at 50 ma 1.502v, .558v I_R at -10v 3.811 μa C_o at V_R = 0 13.61 μμfd.
Vendor E	Signal Transistor	Dwg. No.	I_{cbo} at V_{cdo} = 30v 10μa h_{FE} at V_{CE} = 1v & I_C = 30 ma } 110, 20 $V_{CE}(sat)$ I_C = 30 ma & I_B = 3 ma } 1v, .450v

TABLE 3

STANDARD NOR

Circuit Parameter	Circuit Limits Minimum	Circuit Limits Maximum		Part Conditions for Minimum	Part Conditions for Maximum
V_{BR}	-1.92v	1.31v	E_2	14.4v	9.6v
			V_C	.025v	.455v
			V_D	.462v	.985v
			R_2	3.889K	3.742K
			R_3	19.15K	19.9K
			I_{CO}	0	.210 ma
DOD	.178	16.18	E_1	9.6v	10.8v
			E_2	10.8v	9.6v
			V_C	.15v	1.592
			V_D	.462	.985v
			I_1	.853 ma	0
			I_{CO}	.210 ma	0
			V_{BF}	.75v	.59v
			β	14	140
			R_1	3.889K	3.742K
			R_2	3.889K	3.742K
			R_3	19.15K	19.9K
			R_1'	3.742K	3.889K
			R_2'	3.889K	3.742K
			R_3'	19.9K	19.15K

APPENDIX A

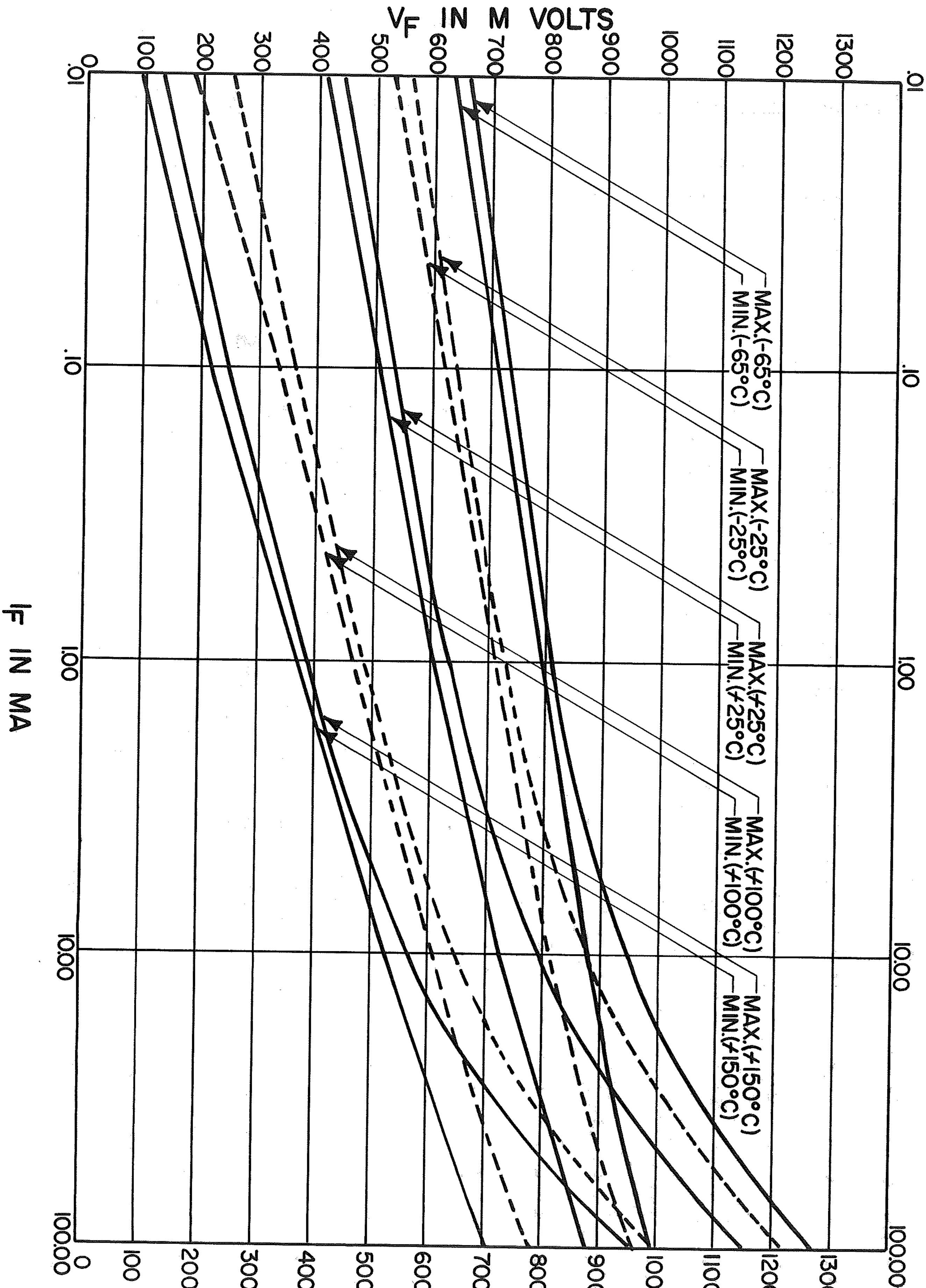
EXPLANATION OF STATISTICS

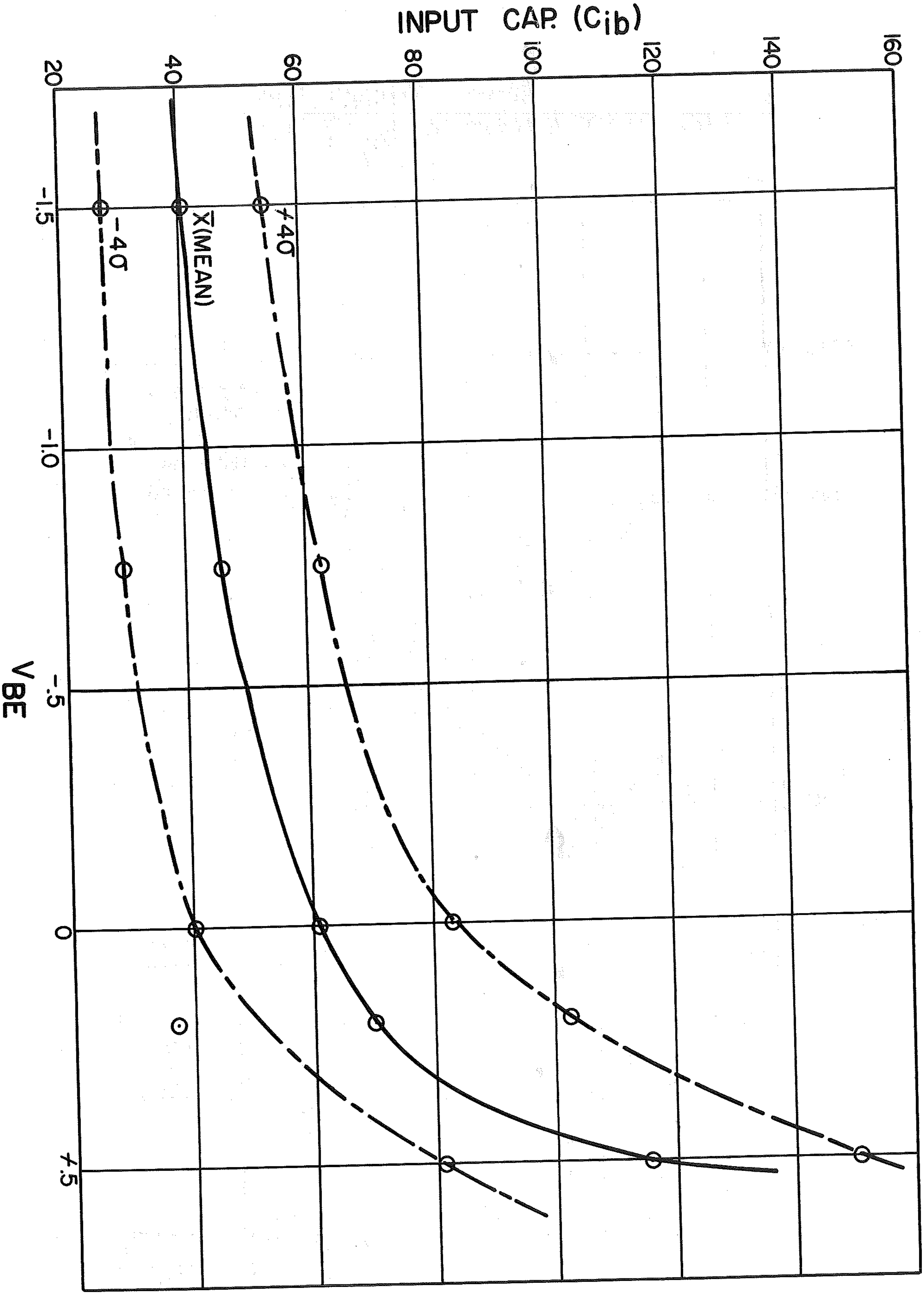
Symbol	Definition
N	Number of samples used for the test.
$\overline{X}$	The mean value, calculated from: $\overline{X} = \frac{\sum_{i=1}^{n} xi}{N}$
S^2	Variance, calculated from: $S^2 = \frac{\sum_{i=1}^{n} xi^2 - N\overline{x}^2}{N - 1}$
S	Standard deviation, equal to the square root of the variance.
Range	The span of the data, calculated from: Range = x max - x min
Min	The minimum value recorded.
Max	The maximum value recorded.
V	The coefficient of variation, in percent, calculated from: $V = \frac{100S}{\overline{X}}$
S_ϵ	Standard error, calculated from: $S_\epsilon = \sqrt{\frac{S^2}{N}}$
α_3	Momental skewness, calculated from: $\alpha_3 = \mu 3/S^3$
β_1	A measure of skewness, calculated from: $\beta_1 = \mu 3^2/\mu 2^3$
β_2	Kurtosis, calculated from: $\beta_2 = \mu 4/\mu 2^2$
$\mu 3$	Third moment about the mean, calculated from: $\mu 3 = \frac{\sum_{i=1}^{n} (xi - \overline{X})^3}{N}$
$\mu 4$	Fourth moment about the mean calculated from: $\mu 4 = \frac{\sum_{i=1}^{n} (xi - \overline{X})^4}{N}$

APPENDIX B

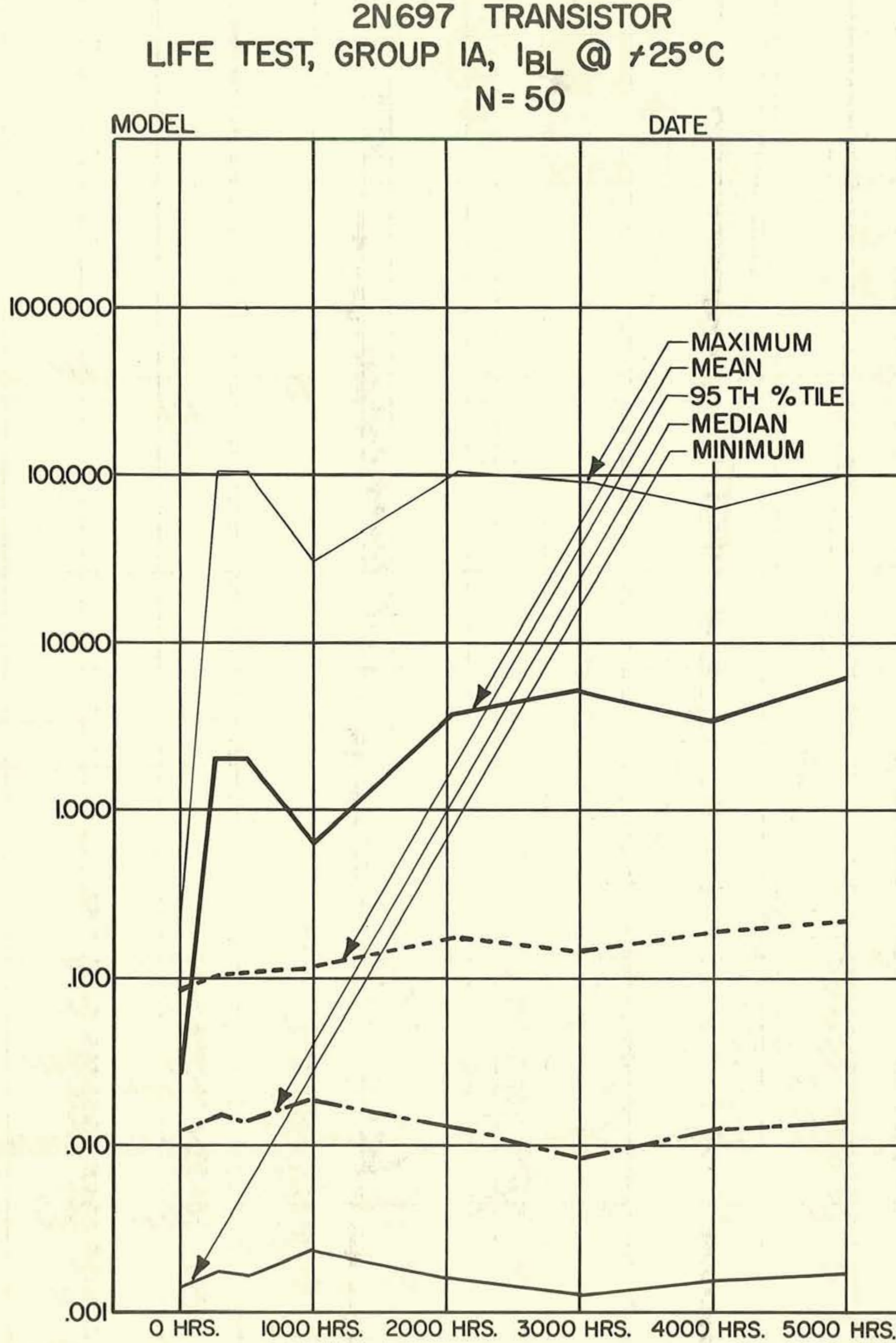
LIST OF SYMBOLS AND DEFINITIONS

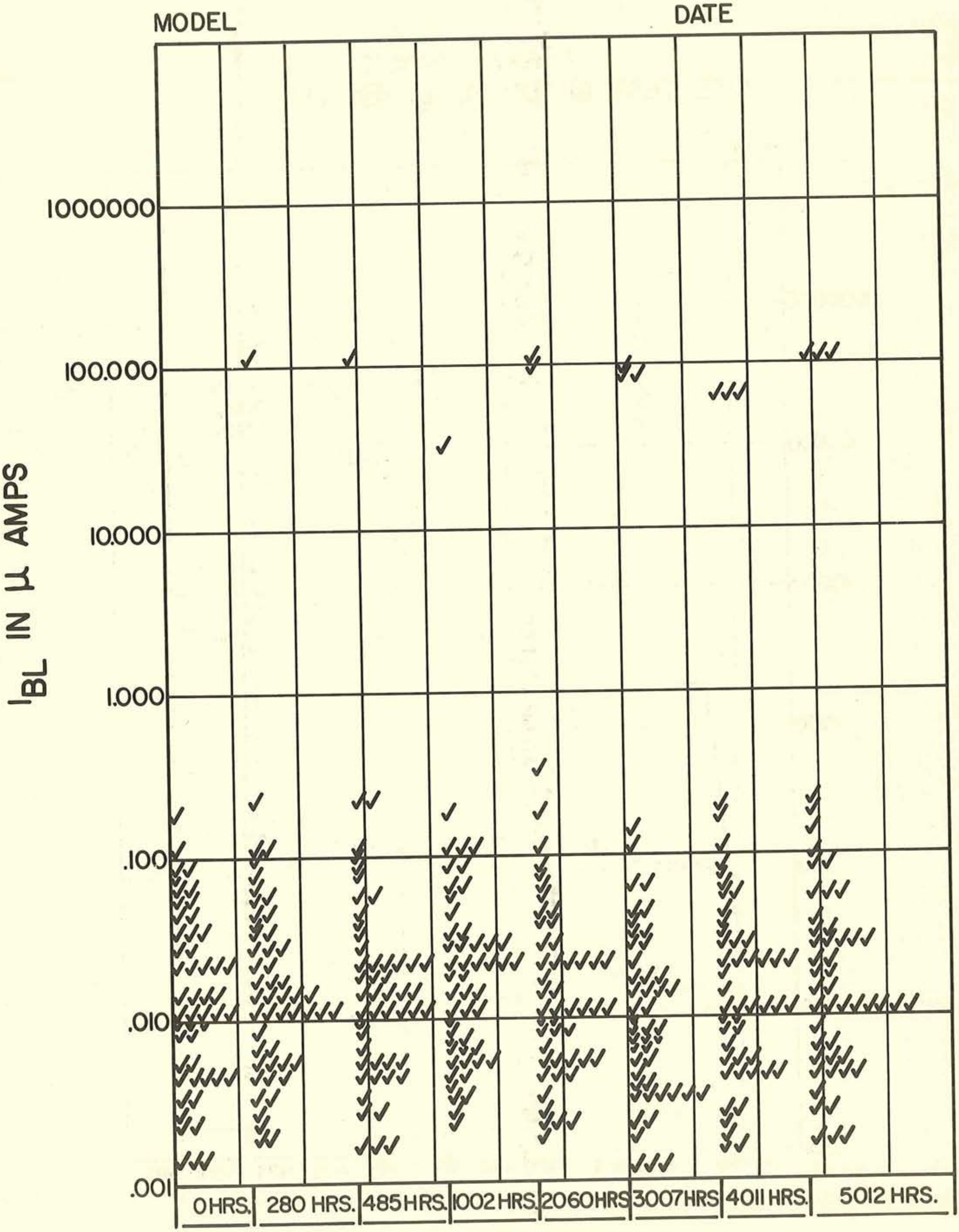
Symbol	Definition
H_{FE} or β	DC current gain of a transistor
V_{CE}	Collector to emitter voltage drop of a transistor at saturation
V_{BE}	Base to emitter voltage drop of a transistor at saturation
I_{CER}	Leakage current of the transistor with both junctions (CB & BE) back biased
I_i	Total input leakage of a nor circuit at saturation. Usually the sum of transistor leakage and diode reverse currents. The number of each is established by logic rules.
V_D	Forward voltage drop of a diode
V_{BR}	Base to emitter voltage of the transistor established by the circuit when cutoff is desired.
DOD	Figure of merit of the circuits drive capability defined as $DOD = \frac{H_{FE} I_B}{I_L}$
I_B	Base current of a transistor when saturation is desired.
I_L	Unit load current - a current drain that a nor circuit represents to its source.
I_C	Collector current of transistor at saturation. $I_C = N\ I_L$ where N is the number of units of load a circuit is designed to deliver.

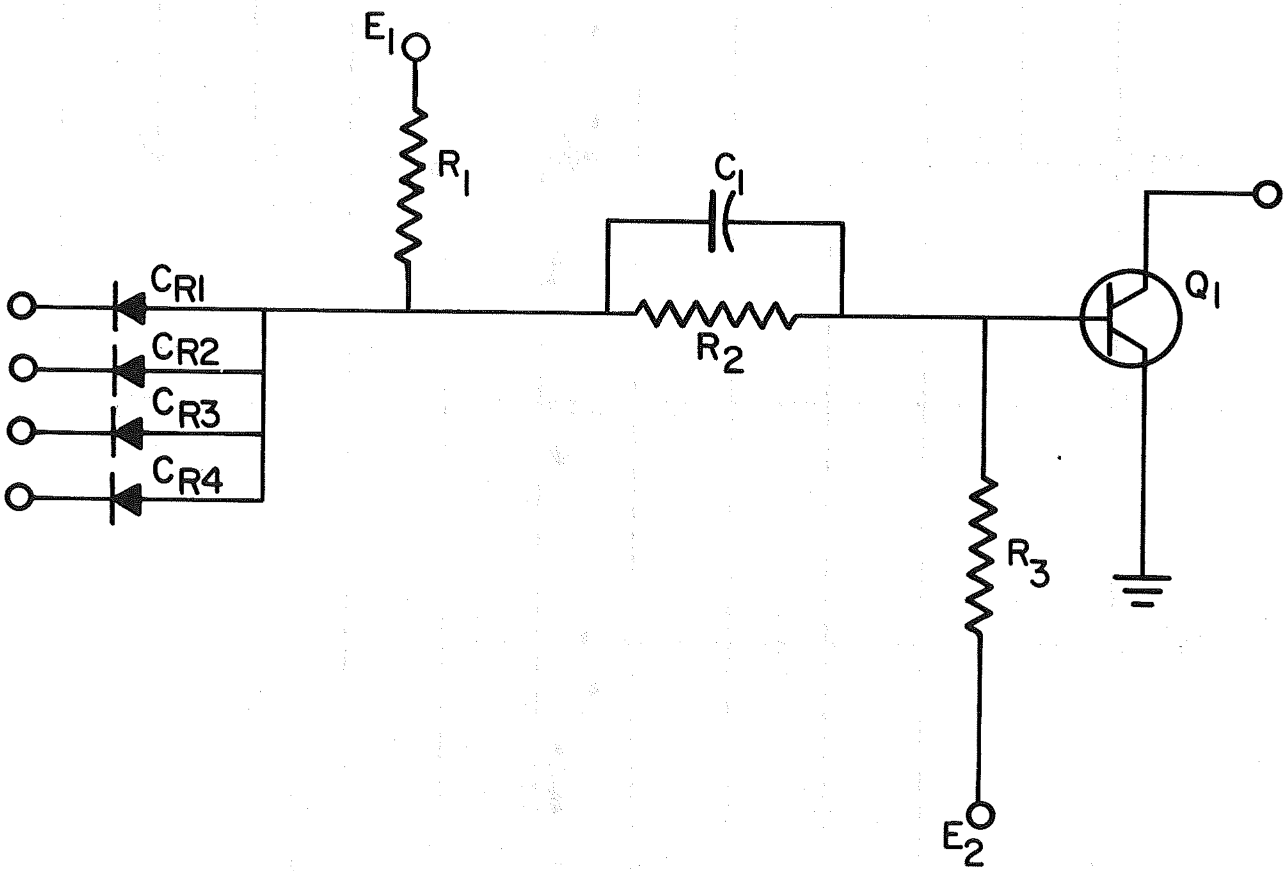

VF IN M VOLTS
IF IN MA
MAX.(-65°C)
MIN.(-65°C)
MAX.(-25°C)
MIN.(-25°C)
MAX.(+25°C)
MIN.(+25°C)
MAX.(+100°C)
MIN.(+100°C)
MAX.(+150°C)
MIN.(+150°C)
.01
.10
1.00
10.00
100.00
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300

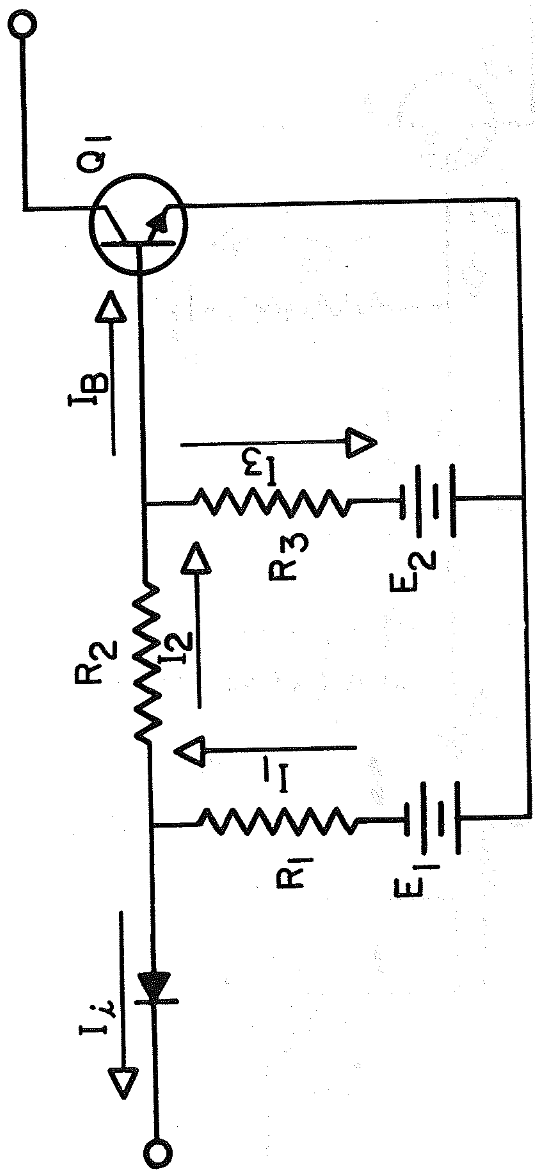


INPUT CAP. (C_{ib})
20
40
60
80
100
120
140
160
V_{BE}
-1.5
-1.0
-.5
0
+.5
+4σ
$\bar{X}$(MEAN)
-4σ

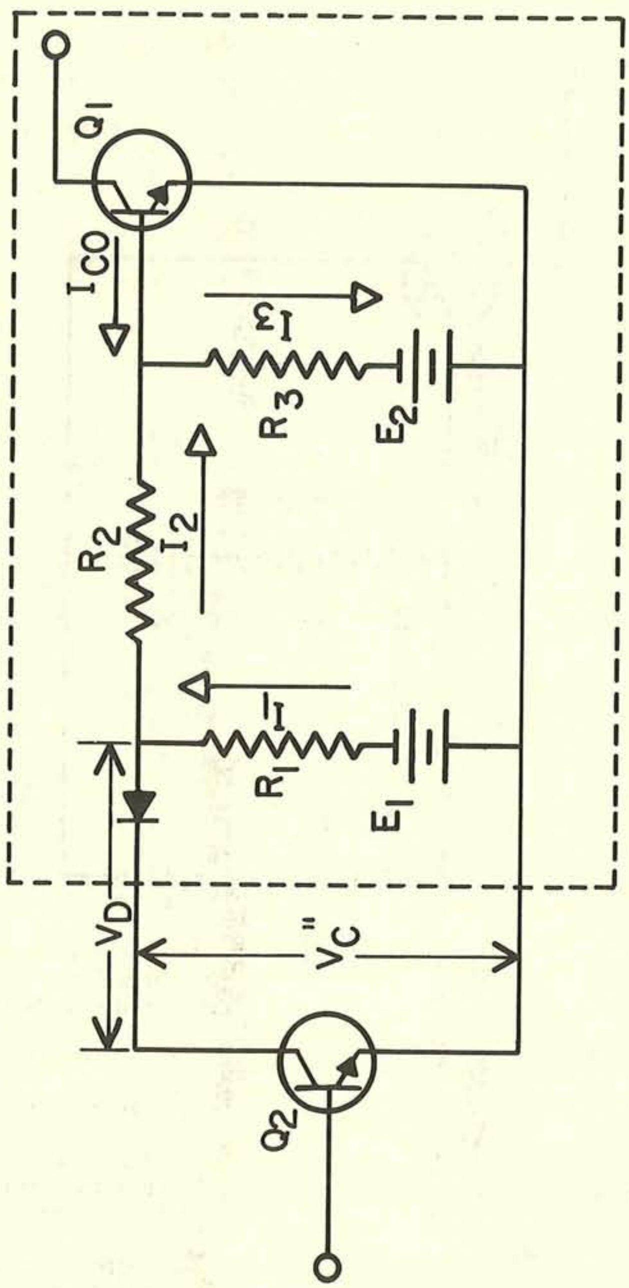

2N697 TRANSISTOR
LIFE TEST, GROUP IA, I BL @ +25°C
N = 50
MODEL
DATE
1000000
100.000
10.000
1.000
.100
.010
.001
MAXIMUM
MEAN
95 TH % TILE
MEDIAN
MINIMUM
0 HRS.
1000 HRS.
2000 HRS.
3000 HRS.
4000 HRS.
5000 HRS.


MODEL
DATE
1000000
100.000
10.000
1.000
.100
.010
.001
I_{BL} IN µ AMPS
0 HRS.
280 HRS.
485 HRS.
1002 HRS.
2060 HRS
3007 HRS
4011 HRS.
5012 HRS.


E1
R1
C1
CR1
CR2
CR3
CR4
R2
Q1
R3
E2



Q1
IB
I3
R3
E2
R2
I2
I1
R1
E1
Ii


Q1
ICO
I3
R3
E2
R2
I2
I1
R1
E1
VD
VC"
Q2

SEVENTH MILITARY-INDUSTRY MISSILE AND SPACE RELIABILITY SYMPOSIUM

18 - 21 JUNE 1962

NAME	ACTIVITY/INDUSTRY
AAKHUS, Robert C.	Minneapolis Honeywell Ordnance Division 600 2nd St. No. Hopkins, Minnesota
AALSETH, Jack Eldon	United Testing Laboratories 150 Wolfe Road Sunnyvale, California
AARON, James Phillip, Jr.	Hercules Powder Company P. O. Box 210 Cumberland, Maryland
ABERNETHY, Robert B.	Pratt & Whitney Aircraft P. O. Box 2691 West Palm Beach, Florida
ADAMOWICZ, Charles M.	Lockheed Missiles & Space Company 510 Middlefield Road Mt. View, California
ADAMS, William R.	BUWEPSFLTREADREP PAC NAS North Island San Diego, California
ALBRIGHT, Donald J.	U. S. Air Force ATC Project Office AF Unit Post Office Los Angeles 45, California
ALLEN, Ethan O.	Bell Aerosystems Company P. O. Box 1 Buffalo 5, New York
ALTHAUS, Edward J.	Hughes Aircraft Co. Florence Avenue & Teale Sts. Culver City, California
AMON, Frank D.	General/Dynamics Pomona, California
AMSBERRY, George H.	Douglas Aircraft Company, Inc. 3000 Ocean Park Boulevard Santa Monica, California
ANDERSON, Robert Harland	Atomics International Box 309 Canoga Park, California
ANDREWS, Chris W.	Douglas Aircraft Company, Inc. 3855 Lakewood Boulevard Long Beach, California
ANKENBRANDT, Francis L.	Radio Corporation of America Defense Electronic Products Building 2-5 Front & Cooper Streets Camden, New Jersey
ARATA, George H.	U. S. Naval Air Test Facility (Ship Installations) U. S. Naval Air Station Lakehurst, New Jersey

NAME	ACTIVITY/INDUSTRY
ARMSTRONG, Charles Vincent	BUWEPSREP 1675 West 5th Street P. O. Box 1011 Pomona, California
ATHERTON, Paul G.	International Telephone & Telegraph Corporation Federal Laboratories Division 500 Washington Avenue Nutley, New Jersey
AUERBACH, Albert	Ryan Aeronautical Company 2701 Harbor Drive San Diego, California
AXEL, Stanford J.	Northrop Ventura 8000 Woodley Avenue Van Nuys, California
AXTELL, Robert C. CAPT, USAF	HQ SSD AFSC Los Angeles, California
BABCOCK, Daniel L.	Solid Propellant Information Agency APL/JHU 8621 Georgia Avenue Silver Spring, Maryland
BAILEY, George R.	General Dynamics/Convair 3302 Pacific Highway San Diego 12, California
BALL, Alpheus M.	Hercules Powder Company Wilmington 99, Delaware
BALL, Leslie Wilson	The Boeing Company Aero-Space Division P. O. Box 3707 Seattle 24, Washington
BALLARD, William E.	U. S. Navy Electronic Laboratory San Diego 52, California
BALLEW, Robert W.	ACIC St. Louis, Missouri
BARBE, Martin	Aerospace Corporation 2400 El Segundo Boulevard El Segundo, California
BARLOW, Edward J.	Aerospace Corporation 2400 El Segundo Boulevard El Segundo, California
BARNES, Curtis H., Jr. LCDR, USN	BUWEPSRESREP Aerojet General Corporation P. O. Box 1947 Sacramento, California
BARRETT, Marvin O.	ATC Project Office AF Unit Post Office Los Angeles 45, California
BARSTOW, Glidden J.	U. S. Navy Electronics Laboratory San Diego 52, California

NAME	ACTIVITY/INDUSTRY
BARTLETT, Parker Morse	The Garrett Corporation 9851 Sepulveda Boulevard Los Angeles 9, California
BARTON, James R.	U. S. Air Force ESD (ESSTE-2) L. G. HANSCOM Bedford, Massachusetts
BAUGH, Charles I.	Emerson Electric Company St. Louis, Missouri
BEALL, Wellwood E.	The Boeing Company P. O. Box 3707 Seattle 24, Wisconsin
BEATON, George N.	Hughes Aircraft Company Florence & Teale Streets Culver City, California
BEAVER, Bud K. CAPT, USN	BUWEPSFLTREADREPPAC NAD North Island San Diego, California
BECKMAN, K. N. COL, USAF	Headquarters United States Air Force Washington, D. C.
BEERS, Robert L. LTCOL, USAF	Air Force Unit Post Office Los Angeles 45, California
BELDEN, Grover	Aerospace Corporation 2400 El Segundo Boulevard El Segundo, California
BELL, Chauncey F.	The Rand Corporation 1700 Main Street Santa Monica, California
BELL, Donald E.	Pratt & Whitney Aircraft Division United Aircraft Corporation 9201 Wilshire Boulevard Beverly Hills, California
BENJAMIN, George C. COL, USA	U. S. Army Maintenance Board Fort Knox, Kentucky
BENNETT, Emory C.	Northrop Corporation Norair Division 1001 East Broadway Hawthorne, California
BENNETT, T. C.	U. S. Naval Air Development Center Johnsville, Pennsylvania
BERGER, Brynjulf	Western Electric Company, Inc. 3300 Lexington Road Winston-Salem, North Carolina
BERKE, H. R. CAPT, USN	U. S. Naval Air Station, North Island San Diego, California
BERMAN, Elliot	U. S. Army Signal R&D Laboratory Fort Monmouth, New Jersey
BETHKE, William P.	Rome Air Development Center Griffiss Air Force Base, New York
BEYER, George L., Jr.	Naval Ordnance Laboratory White Oak, Maryland

NAME	ACTIVITY/INDUSTRY
BINGHAM, Kenneth B.	Douglas Aircraft Company, Inc. 3855 Lakewood Boulevard Long Beach, California
BLACK, Alexander M.	Army Ordnance Missile Command Redstone Arsenal, Alabama
BLACK, Robert O.	Army Ordnance Missile Command Redstone Arsenal, Alabama
BLAIS, Robert A.	Lockheed Missiles & Space Company Palo Alto, California
BLANKS, Eugene H.	Army Ordnance Missile Command Redstone Arsenal, Alabama
BLATT, Milton D.	U. S. Naval Ordnance Test Station Pasadena, California
BLAUVELT, Robert T.	U. S. Army 6087 Sunset Boulevard Hollywood, California
BLUE, William F.	Martin Marrietta Company Waterton, Colorado
BLUHM, Richard W.	The Bendix Corporation Eclipse-Pioneer Division Teterboro, New Jersey
BLUNDELL, Larry	Sperry Utah Company 3211 N. 2100 W. Salt Lake City, Utah
BOHAN, James P.	Sikorsky Aircraft North Main Street Stratford, Connecticut
BOLDEN, Edgar L.	Radio Corporation of America Camden, New Jersey
BOLL, Fred J.	BUWEPSREP Pomona, California
BOOTH, Lionel R. LTCOL, USAF	U. S. Air Force (AFSC) Kirtland Air Force Base, New Mexico
BOOTY, Kelvin H.	U. S. Naval Ordnance Test Station China Lake, California
BOWMAN, Kenneth K.	General Electric Company P. O. Box 8555 Philadelphia, Pennsylvania
BRACHA, Vincent J. LTCOL, USAF	USAF HQ BSD (AFSC) Air Force Unit Post Office Los Angeles 45, California
BRACKETT, Alice Wilson LCDR, USN	U. S. Naval Ammunition Depot Crane, Indiana
BRADLEY, John R.	Douglas Aircraft Company, Inc. Missile & Space Systems Division Santa Monica, California

NAME	ACTIVITY/INDUSTRY
BRASHEAR, Richard H., Jr.	Sperry Utah Company Division of Sperry Rand 322 North 21st West Salt Lake City, Utah
BRELAND, Blish, Jr.	Chance Vought Corporation Box 5907 Dallas 22, Texas
BRENNAN, Francis X.	Wright Patterson Air Force Base Ohio
BRIDGES, James M.	Department of Defense ODD R&E The Pentagon Washington, D. C.
BRIGHAM, Charles W.	Radio Corporation of America Aerospace Communications & Controls Division Junction Routes 3 & 62 Burlington, Massachusetts
BRIMLEY, Donald E.	The Rand Corporation 1700 Main Street Santa Monica, California
BROTHERTON, Theodore W.	General Dynamics/Convair 4297 Pacific Highway San Diego, California
BROUS, Chris J.	Atomics International Division of North American Aviation, Inc. 8900 DeSoto Avenue Canoga Park, California
BROWN, Buford M.	Westinghouse Electric Corporation P. O. Box 1693 Baltimore 3, Maryland
BRYAN, Harold E.	U. S. Navy Electronics Laboratory San Diego 52, California
BRYANT, Herwil M.	U. S. Naval Ordnance Laboratory Corona, California
BRYDIA, Ellis M.	MAAVA Olmsted Air Force Base, Pennsylvania
BRUEGGEMANN, Arthur Rockefeller CDR, USN	Bureau of Naval Weapons Representative 1675 West 5th Street P. O. Box 1011 Pomona, California
BUCHANAN, Robert W.	UNIDYNAMICS Division of Universal Match Corporation 472 Paul Avenue St. Louis 35, Missouri
BUCHELE, Kirwan	Douglas Aircraft Company, Inc. Santa Monica, California
BURNETT, William P.	U. S. Army Redstone Arsenal, Alabama

NAME	ACTIVITY/INDUSTRY
BUSBY, John W.	Sperry Gyroscope Company Great Neck, L.I., New York
BUSSEY, Donald G.	Robins Air Force Base Georgia
BUTLER, Raymond E.	Sandia Corporation P. O. Box 5800 Albuquerque, New Mexico
BUUS, Melvin L.	U. S. Naval Ordnance Laboratory Corona, California
CAMMARATA, John	Arma Division American Bosch Arma Corporation Roosevelt Field Garden City, New York
CAMPBELL, Jerry J.	White Sands Missile Range Standards Laboratory WSMR, New Mexico
CAMPBELL, Richard Sewall	General Dynamics/Astronautics 10544 Challenge Boulevard San Diego, California
CANCILLA, Edward	Douglas Aircraft Company, Inc. 3000 Ocean Park Santa Monica, California
CARLSON, Earl E.	Hughes Aircraft Company P. O. Box 11337 Tucson Division Tucson, Arizona
CARLSON, Roland Philip	Martin Company Friendship International Airport 40, Maryland
CARSON, Albert C. CDR, USN	Defense Electronics Supply Center 1507 Wilmington Pike Dayton, Ohio
CARTER, Maurice McCabe	BUWEPSFLTREADREP PAC NAS North Island San Diego, California
CARY, Raymond John, Jr.	General Dynamics/Electronics P. O. Box 127 San Diego, California
CATE, Albert Murray	United States Air Force Hanscom Field Bedford, Massachusetts
CHANDLER, Earl H.	The Garrett Corporation 9851 Sepulveda Boulevard Los Angeles 9, California
CHANDLER, Robert L.	Marshall Space Flight Center NASA, Huntsville Resdstone Arsenal, Alabama
CHARNOCK, Lester J.	Aeronautical Systems Division Wright Patterson Air Force Base Ohio

NAME	ACTIVITY/INDUSTRY
CHEAK, Donald L.	NAVAVIONICS FAC Indianapolis, Indiana
CHRISTIAN, David B.	General Electric, LMED 831 Broad Street Utica, New York
CHURCH, Edward E.	BUWEPSFLTREADREP Pacific NAS North Island San Diego, California
CLEVELAND, Arthur L.	Directorate of Operational Support Engineering Aeronautical Systems Division Wright Patterson Air Force Base, Ohio
CLINE, Dudley E.	U. S. Army Advent Management Agency Fort Monmouth, New Jersey
CLYMER, Harvey C. LT COL USAF	Ballistic Systems Division, AFSC Air Force Unit Post Office Los Angeles 45, California
COCHRAN, Kenneth	Battelle Memorial Institute 505 King Avenue Columbus 1, Ohio
COFFIN, James C.	U. S. Air Force Systems Command Andrews Air Force Base, Maryland
COHEN, Abraham E.	U. S. Army Advent Management Agency Fort Monmouth, New Jersey
COLE, Richard W.	Applied Physics Laboratory John Hopkins University 8621 Georgia Avenue Silver Spring, Maryland
COLETTA, Arthur P.	Republic Aviation Corporation Farmingdale, New York
COLLINS, Lloyd Raymond	General Dynamics Corporation
COLLINS, Milford E.	Radio Corporation of America 8500 Balboa Boulevard Van Nuys, California
COLLINS, W. M. CAPT USN	U. S. Naval Air Station North Island San Diego 35, California
CONE, Arvine F.	Sandia Corporation Sandia Base Albuquerque, New Mexico
CONNER, Richard M.	ATC Project Office Air Force Unit Post Office Los Angeles 45, California
CONSALVI, Anthony L.	Radio Corporation of America Moorestown, New Jersey
COONEY, Thomas Vincent	NASA Flight Research Center Box 283 Edwards, California
COONS, Donald E.	Headquarters SSD/AFSC DCAS Los Angeles, California

NAME	ACTIVITY/INDUSTRY
CORBIN, Allen M.	U. S. Naval Ordnance Laboratory White Oak Silver Springs, Maryland
COUTINHO, John de S.	Grumman Aircraft Bethpage, L.I., New York
COVINGTON, Garrett C.	McDonnell Aircraft Corporation P. O. Box 516 St. Louis 66, Missouri
COVINGTON, George A.	General Dynamics/Convair P. O. Box 1950 San Diego, California
COX, Charles D.	Army Ordnance Missile Command Redstone Arsenal, Alabama
COX, Paul C.	Ordnance Mission, WSMR White Sands Missile Range, New Mexico
COX, William E.	Northrop Space Laboratory 1111 East Broadway Palos Verdes Estates, California
CRABTREE, David M., Jr.	Rome Air Development Center Griffiss Air Force Base, New York
CULBERTSON, James E.	Western Electric Company, Inc. 3300 Lexington Road Winston-Salem, North Carolina
CULP, Claude R.	Rand Corporation 1700 Main Street Santa Monica, California
CUPO, Ernest P., Jr.	Space Technology Laboratory, Inc. P. O. Box 95001 Los Angeles, California
CURREY, Jake L.	Pacific Missile Range U. S. Naval Missile Center Pt. Mugu, California
DAIGLE, William A.	U. S. Navy Electronics Laboratory San Diego 52, California
DALLMANN, Edwin G.	U. S. Naval Ordnance Laboratory Corona, California
DAMON, Harle Hoyt	General Electric Company Lakeside Avenue Burlington, Vermont
DANCE, Donald W.	U. S. Naval Missile Center Point Mugu, California
DARAY, Jack L. CAPT, USN	U. S. Naval Air Station North Island San Diego 35, California
DARNELL, Paul Stephen	Bell Telephone Laboratory Whippany, New Jersey

NAME	ACTIVITY/INDUSTRY
DAVIDSON, F. F.	PW Department U. S. Naval Air Station North Island San Diego, California
DAVIS, Waymond A. MAJ GEN, USAF	Aeronautical Systems Division Wright Patterson Air Force Base, Ohio
DAVISON, Wayne W.	Collins Radio Company 855-35th Street, NE Cedar Rapids, Iowa
DAWSON, John J.	Aerospace Corporation El Segundo, California
DEFREECE, Dale A.	McDonnell Aircraft Corporation P. O. Box 516 St. Louis 66, Missouri
DEKKER, Albert Orno	Aerojet-General Corporation P. O. Box 1947 Sacramento, California
DELCHAMPS, Thomas B.	Bell Telephone Laboratory Whippany, New Jersey
DELLA-VEDOWA, Richard P.	Lockheed Missiles & Space Company Palo Alto, California
DE YOUNG, Robert L.	U. S Army Ordnance Missile Command Redstone Arsenal, Alabama
DIXON, John E.	BUWEPSFLTREADREP Central Wright Patterson Air Force Base, Ohio
DONAHUE, Philip M.	Bureau of Naval Weapons Representative 400 S. Beiger Street Mishawaka, Indiana
DOSHAY, Irving	Space-General Corporation Subsidiary of Aerojet-General 9200 Flair Drive El Monte, California
DOTEY, Raymond A.	U. S. Army Ordnance District of Los Angeles 55 South Grand Avenue Pasadena, California
DOYLE, Patrick J.	U. S. Naval Ordnance Laboratory Corona, California
DOYLE, Vincent Andrew	North American Aviation, Inc. Los Angeles International Airport Los Angeles 9, California
DOYON, Leonard R.	Raytheon Company Boston Post Road Wayland, Massachusetts
DRAKE, Hubert M.	NAT Aero and Space Administration P. O. Box 273 Edwards, California

NAME	ACTIVITY/INDUSTRY
DRAYNER, Allen H.	Martin Marietta Corporation Martin Company Division Friendship Airport 40, Maryland
DRESSER, Richard L.	Aerospace Defense Systems Office SSD Los Angeles 45, California
DUCHEK, Harold W.	The Emerson Electric Manufacturing Company 8100 West Florissant St. Louis, Missouri
DUESTERBERG, L. C.	The Bendix Corporation Bendix Mishawaka Division 400 S. Beiger Street Mishawaka, Indiana
DUNBAR, Oliver C.	U. S. Army Maintenance Board Fort Knox, Kentucky
DYER, Frank S.	U. S. Naval Air Development Center Johnsville, Pennsylvania
EARLES, Donald R.	AVCO Corporation Wilmington, Massachusetts
EATON, William R.	General Electric Company Space Technology Center Valley Forge, Pennsylvania
EDDINS, Mary F.	AVCO Corporation Wilmington, Massachusetts
EDWARDS, Thomas J.	NASA - MSC Houston 1, Texas
EDZIAK, Theodore F.	Atomics International 8900 DeSoto Avenue Canoga Park, California
EINBINDER, Seymour K.	Picatinny Arsenal Dover, New Jersey
ELLIS, Bernard	Lockheed Missile & Space Company Sunnyvale, California
EMRICH, William F.	Aerojet-General Corporation Azusa, California
ENGQUIST, Earl W.	Sprague Electric Company 12870 Panama Street Los Angeles, California
EPPENSTEIN, Herschel F.	General Dynamics/Astronautics San Diego 12, California
EYLER, William Henry, Jr.	Consolidated Western Steel Division United States Steel Corporation 5700 S. Eastern City of Commerce

NAME	ACTIVITY/INDUSTRY
FALLON, Alex S.	Philco Corporation Subsidiary, Ford Motor Company Western Development Laboratory 3825 Fabian Way Palo Alto, California
FARNSWORTH, William P.	United States Air Force The Pentagon Washington, D. C.
FARRELL, Marvin Royce	BUWEPSFLTREADREP PAC NAS North Island San Diego, California
FATKIN, Thomas J.	BUWEPSFLTREADREP PAC NAS North Island San Diego, California
FEDDERSEN, Edward W.	General Dynamics Corporation San Diego, California
FINE, Aleck	General Electric Company
FINLEY, James Dorsey	United Testing Laboratories 573 Monterey Pass Road Monterey Park, California
FLAGG, Walter L.	United States Air Force Space Systems Division Air Force Unit Post Office Los Angeles 45, California
FLYGARE, Richard W.	Sperry Utah Company Division of Sperry Rand Corporation 322 North 21st West Street Salt Lake City, Utah
FONTAIN, Hubert Louis	Ryan Aeronautical Company 2701 Harbor Drive San Diego, California
FORSMAN, Allyn J.	Minneapolis-Honeywell Regulator Company 2600 Ridgway Road Minneapolis, Minnesota
FORTUNE, William C.	U. S. Naval Air Test Facility Lakehurst, New Jersey
FOX, David H.	Chrysler Corporation 7000 E. Eleven Mile Road Center Line, Michigan
FOX, Kenneth H.	Bendix Corporation Red Bank Division Eatontown, New Jersey
FRANTIK, Rudolph O.	Aerospace Corporation 2400 East El Segundo Boulevard El Segundo, California
FRECH, William Paul	Lockheed-Georgia Company 86 South Cobb Drive Marietta, Georgia

NAME	ACTIVITY/INDUSTRY
FREDERICK, Herbert E.	Aerospace Corporation El Segundo, California
FREEMAN, John F.	Aerojet-General Corporation P. O. Box 1947 Sacramento 9, California
FRASER, James A.	Professor of Physical Science Maxwell Air Force Base, Alabama
FRIEDENREICH, Gilbert	Fairchild Stratos Corporation Spacecraft Systems Bayshore, New York
FRITZ, Harvey Walter	National Aeronautics & Space Administration NASA Representative Office North American Aviation Downey, California
FUNK, Ben I.	Commander SBAMA Norton Air Force Base, California
FURRER, Rudolph	Lockheed Missiles & Space Company Sunnyvale, California
GALIB, Thomas A.	U. S. Naval Underwater Ordnance Station Newport, Rhode Island
GANTT, Richard R. LT COL, USAF	L. G. Hanscom Field Bedford, Massachusetts
GARDINER, Duncan B.	Vickers, Inc. Division Sperry Detroit 32, Michigan
GARDSBANE, Alvin	Astronautics Division Chance Vought Corporation P. O. Box 6267 Dallas 22, Texas
GARMAN, Ralph Sheldon COL USAF	Commander, Air Force Missile Development Center Holloman Air Force Base, New Mexico
GARNER, Norman R.	Aerojet-General Corporation 1100 West Hollyvale Azusa, California
GAVURIN, Edward I.	General Electric Company 3198 Chestnut Street Philadelphia 4, Pennsylvania
GEPHART, Landis S.	Lockheed Missiles & Space Company Sunnyvale, California
GIARRIZZO, Charles	SBAMA Service Engineering Division Directorate of Materiel Management Norton Air Force Base, California
GIBSON, Carl E.	Liquid Propulsion Systems NASA George C. Marshall Space Flight Center Huntsville, Alabama
GIBSON, Charles Edward	Commander, Operational Test & Evaluation Force Norfolk 11, Virginia

NAME	ACTIVITY/INDUSTRY
GILL, John F.	Aerojet-General Corporation 1100 W. Hollyvale Avenue Azusa, California
GLICKMAN, Lester	Navy Central Torpedo Office Newport, Rhode Island
GLIDDEN, Bruce	Consolidated Western Steel Division United States Steel Corporation P. O. Box 2015 Terminal Annex Los Angeles 54, California
GODSEY, Jack C.	Thiokol Chemical Huntsville, Alabama
GOLDBERG, Morton E.	Armour Research
GOLDENRATH, Walter Lewis CDR, USN	U. S. Naval Air Station North Island San Diego 35, California
GOODHART, Milton E.	Marquardt Corporation 16555 Saticoy Street Van Nuys, California
GRAINGER, George R.	Planning Research Corporation 1333 Westwood Boulevard Los Angeles 24, California
GRAY, William L.	The Boeing Company P. O. Box 3707 Seattle 24, Washington
GREER, Richard D., Jr. CDR, USN	BUWEPSFLTREADREP PACIFIC NAS North Island San Diego, California
GREGORY, Lowell D.	Chance Vought Corporation Ling-Temco-Vought, Inc. P. O. Box 5003 Dallas 22, Texas
GREGORITS, Robert F.	Bureau of Naval Weapons Representative 400 S. Beiger St. Mishawaka, Indiana
GREMBAN, Walter A.	ATC Project Officer Air Force Unit Post Office Los Angeles 45, California
GRUOL, John W.	U. S. Army Signal R&D Laboratory Fort Monmouth, New Jersey
HADDEN, Leonard John	The Marquardt Corporation 16555 Saticoy Street Van Nuys, California
HADLEY, William Lee	Martin Company Baltimore 3, Maryland
HAGAN, John Thomas	Martin Company
HAGE, Harry Dennis	BUWEPSFLTREADREP PACIFIC NAS North Island San Diego 35, California

NAME	ACTIVITY/INDUSTRY
HAIGLER, William B.	ROCKETDYNE Division of North American Aviation, Inc. 6633 Canoga Park, California
HALL, Charles M.	Aerojet-General Corporation 11711 Wooddruff Avenue Downey, California
HALL, Donald P.	Air Force Flight Test Center EDWARDS Air Force Base, California
HALL, Lacey C.	San Bernardion Air Material Area Norton Air Force Base, California
HAMMELL, Richard	Bell Telephone Laboratories Whippany Road Whippany, New Jersey
HAMMERS, Fred Charles	NASA, Marshall Space Flight Center HUNTSVILLE, Alabama
HAMONTRE, Hugh Clayton	Naval Weapons Laboratory Corona, California
HANSSEN, Gustav F.	U. S. Army Ordnance District 4300 Goodfellow Boulevard St. Louis, Missouri
HARDENBAURGH, Miles R.	CG AOMC Redstone Arsenal, Alabama
HARMEN, Raymond A.	Commander, Naval Missile Center Pacific Missile Range Point Mugu, California
HARN, Gene Laverne	ATC Project Office Air Force Unit Post Office Los Angeles 45, California
HARNETT, Daniel Edward	General Electric Company Charles Building Liverpool, New York
HARTER, Wendell W.	Northrop Norair 1001 East Broadway Hawthorne, California
HARTVIGSEN, Donald E.	Aerojet-General Corporation 1100 W. Hollyvale Azusa, California
HASSLER, Kenneth E.	Battelle Memorial Institute 5050 King Avenue Columbus, Ohio
HAWKINS, Willis M.	Lockheed Missiles & Space Company Sunnyvale, California
HEATH, Robert Lowrey	North American Aviation, Inc. Rocketdyne Division 6633 Canoga Avenue Canoga Park, California
HENDERSON, George Andrew	Martin Company Orlando, Florida

NAME	ACTIVITY/INDUSTRY
HENNING, Frederick W.	Westinghouse Electric Corporation Astronuclear Laboratory P. O. Box 10864 Pittsburg 36, Pennsylvania
HENRY, George Edwin	General Electric Company Ordnance Department Pittsfield, Massachusetts
HERD, G. Ronald	Booz Allen Applied Research, Inc. 4815 Rugby Avenue Bethesda, Maryland
HIBBARD, Hall Livingston	Lockheed Aircraft Corporation Burbank, California
HINKLE, Mark L.	General Electric LMED 901 Broad Street Utica, New York
HIPPS, William Grover	Tactical Air Command Langley Air Force Base, Virginia
HIRSCHRON, Martin	Industrial Acoustics Company 341 Jackson Avenue New York 54, New York
HOCHMAN, Daniel	Lockheed Missiles and Space Company
HOESEL, Neil E.	Thiokol Chemical Corporation Brigham City, Utah
HOLLAND, John	American Bosch Arma Corporation Arma Division San Diego, California
HOLLMAN, Dallas Joseph	General Dynamics/Astronautics Box 1128 San Diego 12, California
HOLLORAN, Ralph P.	North American Aviation, Inc. Columbus 16, Ohio
HOLSCLAW, Gerald R.	HQ AFLC WFAFB, Ohio
HOMSY, A. A.	Litton Systems, Inc. Woodland Hills, California
HORN, George Martin	U. S. Naval Ordnance Test Station China Lake, California
HUGHES, Thomas Edge	Defense Research Laboratories General Motors Corporation 6767 Hollister Avenue Goleta, California
HURST, James Harris	NASA Marshall Space Flight Center Huntsville, Alabama
HURST, Richard M.	U. S. Army Ordnance Missile Command Redstone Arsenal, Alabama
HUTCHINS, Guy Vernon	BUWEPSFLTREADREP PACIFIC NAS North Island San Diego 35, California

NAME	ACTIVITY/INDUSTRY
HUTCHINS, Harold J.	USAF SBAMA Norton Air Force Base, California
HUTTON, Lenard Ray	U. S. Naval Ordnance Laboratory Corona, California
IVES, George Stoughton	Bureau of Naval Weapons Representative Pomona, California
INMAN, William R.	U. S. Naval Ammunition Depot Crane, Indiana
IRVINE, Clarence S.	AVCO Corporation Suite 400 8939 South Sepulveda Boulevard Los Angeles 45, California
ISRAEL, Edmund M.	Space Technology Laboratory, Inc. One Space Park Redondo Beach, California
JABLONSKI, Frank E.	National Aeronautics & Space Administration 1520 H Street, N.W. Washington, D. C.
JACOBS, Leonard	Radio Corporation of America 8500 Balboa Boulevard Van Nuys, California
JAHR, Edgar F.	IBO Corporation Owego, New York
JAKOBOWSKI, Walter	National Aeronautics & Space Administration 1520 H Street, N. W. Washington, D. C.
JAMES, Don	General Dynamics 1675 West 5th Street Pomona, California
JOHNSON, Bernie D. LT COL TC, USA	Department of the Army Utah General Depot Ogden, Utah
JOHNSON, Edwin Harold	U. S. Naval Ordnance Laboratory Corona, California
JOHNSON, Curt I.	IBM Corporation Owego, New York
JOHNSON, Francis B.	Lockheed Missile & Space Company
JOHNSON, LaVern M.	Naval Ordnance Laboratory Corona, California
JOHNSON, Ross Herman	Martin Marietta Corporation Baltimore 3, Maryland
JOHNSON, William F.	Curtiss-Wright Corporation Caldwell, New Jersey
JONES, Earl L.	North American Aviation, Inc. International Airport Los Angeles, California

NAME	ACTIVITY/INDUSTRY
JONES, Edward E.	Bureau of Naval Weapons Washington, D. C.
JONES, Robert Edward	NASA Marshall Space Flight Center Huntsville, Alabama
JOYNER, James L.	National Aeronautics & Space Administration Cape Canerval, Florida
JOYNER, Ronald S. 2nd LT USAF	ASD AFSC Wright-Patterson Air Force Base, Ohio
KAPLAN, Irving E.	U. S. Naval Personnel Research Activity San Diego 52, California
KAMINS, Milton	The Rand Corporation 1700 Main Street Santa Monica, California
KARMIOL, Edwin D.	General Electric Company 3198 Chestnut Street Philadelphia, Pennsylvania
KAUDER, Arnold J.	Bureau of Naval Weapons Representative North Hollywood 11600 Sherman Way North Hollywood, California
KEAR, Donald L.	Defense Electronics Supply Center 1507 Wilmington Pike Dayton, Ohio
KEEFE, Gordon J.	Defense Supply Agency Inspection & Quality Control Division, P&P Directorate, Defense Supply Agency Room 2807 Tempo A Washington, D. C.
KELLY, Robert B. LT COL, USAF	Air Force Plant Representative Air Force Systems Command General Dynamics/Astronautics P. O. Box 1128 San Diego 12, California
KENNA, William E.	Sikorsky Aircraft Stratford, Connecticut
KENT, James R.	U. S. Naval Ammunition Depot Crane, Indiana
KIMEL, Harry	General Electric Company Philadelphia, Pennsylvania
KIMBERLIN, John I.	U. S. Air Force Inspector General Norton Air Force Base, California
KIRK, Gerald A.	Loral Electronics Corporation 825 Bronx River Avenue New York, New York
KISSINGER, Milan P. H.	Ryan Aeronautical Company Lindbergh Field San Diego 12, California

NAME	ACTIVITY/INDUSTRY
KLINE, William Darwin	U. S. Naval Ammunition Depot Crane, Indiana
KLINGON, Arthur J.	COMFLDCOM DASA Sandia Base, New Mexico
KNIGHT, Chester Raymond	ARINC Research Corporation 1700 K Street, N. W. Washington, D. C.
KNORR, Harold M.	Douglas Aircraft Company 300 Ocean Park Boulevard Santa Monica, California
KNUDSEN, George E.	Temco Electronics Division Box 6118 Dallas 22, Texas
KOCH, James R.	Minneapolis-Honeywell Aero Division 13350 U. S. Highway 19 St. Petersburg, Florida
KOONTZ, Warren S.	Bureau of Naval Weapons Washington, D. C.
KOPCSAK, Arpad A. COL USA	Headquarters, Department of the Army Office of the Deputy Chief of Staff for Military Operations Washington, D. C.
KOPPENHAVER, James T.	National Aeronautics and Space Administration 400 Maryland Avenue Washington, D. C.
KRAUS, John W.	Atomics International 8900 De Soto Avenue Canoga Park, California
KRAVA, Roy "A"	General Dynamics/Convair San Diego, California
KREBBERS, Johannes	Stanford Research Institute 333 Ravenswood Avenue Menlo Park, California
KREUZE, Floyd Jay	Lear, Inc. Instrument Division 110 Ionia Avenue, N.W. Grand Rapids, Michigan
KRZYSIAK, Edward F.	Rome Air Development Center Griffiss Air Force Base, New York
KUNZ, Earl Greaves	North American Aviation, Inc. Los Angeles, California
LAMB, William Xavier	The Bendix Corporation Bendix-Pacific Division Sherman Way North Hollywood, California
LAMBERTINE, Joseph A.	The Bendix Corporation Fischer Building Detroit 2, Michigan

NAME	ACTIVITY/INDUSTRY
LAMKIN, Lessel Edwin	Sandia Corporation Sandia Base Albuquerque, New Mexico
LAMONT, Kenneth O.	The Bendix Corporation Bendix Mishawaka Division 400 S. Beiger Street Mishawaka, Indiana
LANGSTON, James T. LCDR, USN	U. S. Naval Air Station North Island San Diego, California
LANGIE, Henry J.	Aeronutronic Division Ford Motor Company Ford Road Newport Beach, California
LAURICH, James A. CAPT, USN	BUWEPSFLTREADREP Pacific NAS North Island San Diego, California
LAWSON, Lawrence G.	General Dynamics/Convair 3302 Pacific Highway San Diego, California
LEBRE, Edward G.	Raytheon Company Spring Street Lexington 73, Massachusetts
LEE, James B.	U. S. Army Signal Supply Agency 125 South Grand Avenue Pasadena, California
LEHR, Samuel N.	Space Technology Laboratory, Inc. One Space Park Redondo Beach, California
LENNON, Robert A.	General Dynamics 5th Street Pomona, California
LEMIEUX, Norman LCDR, USN	OPTEVFORPAC NAS North Island San Diego, California
LESHER, Charles M. LT, USNR-R	COMELEVEN San Diego 30, California
LIGHTER, Nathan	Gruman Aircraft Engineering Corporation Bethpage, New York
LINDSAY, Griffith W.	Aeronautical Systems Division Wright Patterson Air Force Base, Ohio
LITTLER, Richard C.	Headquarters, Air Force Logistics Command Wright-Patterson Air Force Base, Ohio
LLOYD, David K.	Space Technology Laboratory One Space Park Redondo Beach, California
LOUGH, Thomas M.	Space Technology Laboratories, Inc. 1 Space Park Redondo Beach, California

NAME	ACTIVITY/INDUSTRY
LOWERS, Horace R.	U. S. Army Ordnance Missile Command Redstone Arsenal, Alabama
LUBELSKY, Benjamin Louis	Lockheed Missiles & Space Company Sunnyvale, California
MAAS, Arthur V.	Bureau of Naval Weapons Resident Representative P. O. Box 157 Magna, Utah
MacCARLEY, John A.	Lockheed-California Company Burbank, California
MACHONGA, John G.	The Pyle-National Company 1334 N. Kostner Avenue Chicago 51, Illinois
MADDEN, James H.	Aerojet General Corporation P. O. Box 1947 Sacto, California
MADDOX, Wilkes L.	McDonnell Aircraft Corporation Box 516 St. Louis 66, Missouri
MALKIN, Samuel	U. S. Army Signal Materiel Support Agency Fort Monmouth, New Jersey
MARQUARDT, Lester S.	U. S. Naval Missile Center Point Mugu, California
MARSHALL, William E.	Minneapolis Honeywell Ordnance Division 600 2nd Street, North Hopkins, Minnesota
MARTIN, William J.	General Dynamics/Convair 3302 Pacific Highway San Diego 12, California
MASON, John E.	Naval Torpedo Station Keyport, Washington
MASTERSON, K. S. RADM, USN	Deputy Chief, Bureau of Naval Weapons Constitution Avenue, N.W. Washington, D. C.
MATTHES, Walter L.	Martin Company Orlando, Florida
MAY, Britt S. COL, USAF	Warfare Systems School Maxwell Air Force Base, Alabama
MC ADAM, John Cullen	International Electronic Research Corporation 135 West Magnolia Boulevard Burbank, California
MC AULIFFE, William I.	AiResearch Manufacturing Company Division of the Garrett Corporation 9851 Sepulveda Boulevard Los Angeles, California

NAME	ACTIVITY/INDUSTRY
MC BRIDE, Jack E.	Department of the Navy 18th & Constitution Avenue, N.W. Washington, D. C.
MC CAFFREY, Frank K.	General Dynamics/Pomona Pomona, California
MC CASLIN, Louis B.	ARINC Research Corporation 467 Hamilton Avenue Palo Alto, California
MC CLAY, Max Ivan	Bureau of Naval Weapons Representative Pomona, California
MC CLEARY, George C. LT COL, USAF	U. S. Air Force Inspector General Norton Air Force Base, California
MC CLINTIC, Robert G.	U. S. Army; DA Information 6087 Sunset Boulevard Hollywood, California
MC CLURE, Hulius Y.	General Dynamics Corporation P. O. Box 2672 San Diego 12, California
MC CORMACK, Charles K.	Oregon Precision Industries, Inc. 125 E. 34th Street Albany, Oregon
MC DONALD, Joseph J.	BUWEPSFLTREADREP Pacific NAS North Island San Diego, California
MC DUFFEE, Paul E.	Philco Corporation Western Development 3875 Fabian Way Palo Alto, California
MC GOWAN, Allen P.	U. S. Naval Ordnance Laboratory Corona, California
MC KAY, Robert R.	Headquarters, Air Force Logistics Command Wright-Patterson Air Force Base Dayton, Ohio
MC LAUGHLIN, Charles E.	Aeronautical Systems Division Wright-Patterson Air Force Base, Ohio
MC MASTER, Alexander C.	General Dynamics P. O. Box 1011 Pomona, California
MC MICHAEL, Eugene	Headquarters, Department of the Army Chief Signal Officer Washington, D. C.
MELARA, Philip	Grumman Aircraft Engineering Corporation Bethpage, New York
MENELEY, Carl A.	Goodyear Aircraft Corporation 1210 Massillon Road Akron, Ohio
MERKEL, Albert G.	BUWEPSFLTREADREP Pacific NAS North Island San Diego, California

NAME	ACTIVITY/INDUSTRY
MEYER, Joseph Simon	Litton Systems, Inc Woodland Hills, California
MEYER, Richard A.	General Electric 1000 Western Avenue, W. Lynn, Massachusetts
MICHELS, William N.	Headquarters, SSD AFSC Los Angeles, California
MILLER, George J.	Hughes Aircraft Company P. O. Box 2097 Fullerton, California
MOAN, Obert B.	Lockheed Missiles & Space Company Sunnyvale, California
MONTGOMERY, Paul B.	General Dynamics/ Convair Division San Diego, California
MOORE, Edwin F.	North American Aviation McGregor, Texas
MOORE, John R.	North American Aviation, Inc. Autonetics Division 9150 E. Imperial Highway Downey, California
MOORE, W. R., Jr.	Administrative Officer U. S. Naval Air Station NAS North Island San Diego, California
MORELAND, Robert A.	U. S. Naval Missile Center Point Mugu, California
MORRIS, Brooks T.	California Institute of Technology Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California
MORRISON, Edward J.	Texas Instruments, Inc. 6000 Lemmon Avenue Dallas, Texas
MOTE, Amos M. LT COL	APGC Eglin Air Force Base, Florida
MOYNIHAN, John D.	Sprague Electric Company Marshall Street North Adams, Massachusetts
MRAZ, John Z.	Air Force Plant Representative Air Force Systems Command General Dynamics/Astronautics San Diego 12, California
MUELLER, Richard Albert	General Dynamics Corporation
MULKERN, John R.	Bureau of Naval Weapons Representatives (SPO), LMSC Box 504 Sunnyvale, California
MULOCK, Richard B.	Sylvania 1100 Wehrle Drive Buffalo, New York

NAME	ACTIVITY/INDUSTRY
MURCHISON, Weldon O.	U. S. Air Force Inspector General Norton Air Force Base, California
MURPHY, J. F.	PW Department U. S. Naval Air Station, North Island San Diego, California
MURPHY, Ray B.	Bell Telephone Laboratories, Inc. 463 West Street New York 14, New York
MUTER, Joseph J.	United States Army OCOFT, Building T-7 Washington 25, D. C.
MYERS, Richard H.	Hughes Aircraft Company Florence & Teale Streets Culver City, California
NASSER, Francis E.	U. S. Navy Central Torpedo Office Newport, Rhode Island
NATELSON, David Myles	Loral Electronics Corporation 825 Bronx River Avenue New York, New York
Naubereit, Henry	Aero Electronic & Electrical Laboratory NAD Crane, Indiana
NAVOY, Anthony J.	General Atomic Division General Dynamics Corporation P. O. Box 608, San Diego 12, California
NEAL, William W	The Martin Company Orlando, Florida
NEWBERG, Eric G.	The Boeing Company Aerospace Division P. O. Box 3707 Seattle 24, Washington
NEWBERRY, Billy Dean	General Dynamics Corporation
NIEWOOD, Harry	American Machine & Foundry Company 11 Bruce Place Stamford, Connecticut
NOOTZ, Willard E.	Aeronautical Systems Division Wright Patterson Air Force Base, Ohio
NORMAN, Barry R.	Whle Laboratories 128 Maryland St. El Segundo, California
NORRIS, Rollin H.	General Electric Company 1 River Road Schenectady, New York
NOSLEY, Charles C.	Sundstrand Aviation 2421 11th Street Rockford, Illinois

NAME	ACTIVITY/INDUSTRY
NOWAK, Laurance H.	Lockheed Propulsion Company P. O. Box 111 Redlands, California
NUCCI, Elidio J.	STAFF Assistant Office of Maintenance Engineering Office of Director of Defense Research and Engineering Washington, D. C.
NYBURG, Willard L.	U. S. Navy OJCS, JT. Staff J-5 AE&GM Branch
NYLAND, Frederic S.	The Rand Corporation 1700 Main Street Santa Monica, California
OAKLEY, Paul D.	Department of the Army Diamond Ordnance Fuze Laboratories Washington 25, D. C.
O'CONNELL, Edison E	COMPACMISRAN
O'CONNELL, Edmund P.	Gederal Electric Corporation 621-671 Industrial Avenue Paramus, New Jersey
O'KEEFE, John T.	U. S. Army Ordnance Missile Command Redstone Arsenal, Alabama
OLIVER, Richard Maxey	Aerospace Industries Association of America, Inc. 610 Shoreham Boulevard Washington 5, D. C.
OLON, Frederick A.	U. S. Naval Propellant Plant Indian Head, Maryland
OLSEN, Emil M.	The Garrett Corporation 9851 Sepulveda Boulevard Los Angeles 9, California
OLSON, Curtis L.	USA Engineering Res & Dev Laboratories Ft. Belvoir, Virginia
O'NEAL, Russell D.	The Bendix Corporation 1104 Fisher Boulevard Detroit 2, Michigan
ORKIN, Fredric I.	Electro-Mechanical Research, Inc. P. O. Box 3041 Sarasota, Florida
ORR, Robert R.	NASA Geo C. Marshall Space Flight Center Huntsville, Alabama
OTTOBRE, James	Lockheed Electronics Company U. S. Highway 22, Plainfield, New Jersey
PABST, William R., Jr.	Bureau of Naval Weapons Washington, D. C.

NAME	ACTIVITY/INDUSTRY
PAIGE, Hilliard W.	General Electric Company Missile & Space Vehicle Department P. O. Box 8555 Philadelphia 1, Pennsylvania
PAINTER, Brookman R.	Western Regional Officer Army Signal Supply Agency 125 South Grand Pasadena, California
PALMER, Richard E.	The Garrett Corporation AiResearch Manufacturing Company 9851 Sepulveda, Los Angeles Los Angeles, California
PANG, KaLun	BUWEPSFLTREADREP Pacific NAS North Island San Diego, California
PARK, August R.	GPI Librascope Division Aerospace Branch 1370 Encinitas Road San Marcos, California
PEARLIN, Leo R.	Lockheed California Company P. O. Box 551 Burbank, California
PENNELL, Alfred R.	Motorola, Inc. MED/WC 8201 E. McDowell Road Scottsdale, Arizona
PERAPNO, G. S.	Headquarters, U. S. Air Force Washington, D. C.
PERRIN, Robert Wayne	General Dynamics/Astronautics San Diego, California
PERRY, Lucius A., Jr. COL USAF	6595th Aerospace Test Wing, AFSC Vandenberg Air Force Base, California
PETERSEN, Clifford C.	Motorola, Inc. Scottsdale, Arizona
PETERSON, Mell A.	Northrop Corporation 9744 Wilshire Boulevard Beverly Hills, California
PETERSON, Robert L.	Opn Analysis, Headquarters SAC Offutt Air Force Base, Nebraska
PEWITT, James D. CAPT, USAF	SBAMA Norton Air Force Base, California
PICKER, Walter J.	GPI Librascope Division 808 Western Avenue Glendale, California
PICKREL, Evan Wilken	Douglas Aircraft Company Santa Monica, California
PILIGIAN, Murad S.	U. S. Air Force ESD L. G. Hanscom Field Bedford, Massachusetts

NAME	ACTIVITY/INDUSTRY
PLISKIN, Daniel	Grumman Aircraft Engineering Corporation
POLLOCK, Robert D.	The Marquardt Corporation 2771 N. Carey Avenue Pomona, California
PONTIOUS, Harry Lowell	North American Avn. Inc. Downey, California
PORTER, David C.	The Boeing Company P. O. Box 3707 Seattle 24, Washington
PORTER, Roy Vernon	Office Chief of Research & Development, DA Room 3E-364 The Pentagon Washington, D. C.
PORTNER, Ferris Dale	U. S. Naval Propellant Plant Indian Head, Maryland
POUNDER, Edwin	Jet Propulsion Laboratory Pasedena, California
POWELL, Harry Rutter	Space Technology Laboratory, Inc. P. O. Box 95001 Los Angeles 45, California
POWERS, Aaron B.	U. S. Naval Ordnance Laboratory Corona, California
PROCTOR, Phimister B.	Hughes Aircraft Company Florence & Teale Streets Culver City, California
PUTT, Gldyn H.	Lockheed Missiles & Space Company P. O. Box 504 Sunnyvale, California
RABEY, Duncan W.	6595th Aerospace Test Wing AFSC Vandenberg Air Force Base, California
RAGSDALE, Milton M.	ARINC Research Corporation 1700 K Street N. W. Washington, D. C.
RAPP, Edward G.	Aerojet General Corporation P. O. Box 1947 Sacramento, California
RASNICK, Ben	COMPACMISRAN
RAYMOND, George A.	Remington Rand Univac St. Paul 16, Minnesota
REED, Douglas A.	AiResearch Manufacturing Company of Arizona 402 South 36th Street Phoenix, Arizona
REEVE, Edward A.	IBM Corporation Owego, New York
REITER, Harry L. RADM	The Pentagon Washington, D. C.
REITER, Philip	Aerojet-General Corporation

NAME	ACTIVITY/INDUSTRY
REYNOLDS, Robert Max	Force Material Officer Staff, COMNAVAIRPAC NAS North Island San Diego, California
RICHARDSON, Norval Ralph	BUWEPSFLTREADREP Pacific NAS North Island San Diego, California
RICHMOND, Donald Eugene	Texas Instruments, Inc. 6000 Lemmon Avenue Dallas, Texas
RILEY, William E.	Battelle Memorial Institute 505 King Avenue Columbus, Ohio
RIORDAN, John J.	Office of the Secretary of Defense Room 4B684 The Pentagon Washington, D. C.
RISINGER, Ben Weir	Ling Temco Vought Aeronautics Division Box 5907 Dallas, Texas
RITCHEY, Harold W.	Thiokol Chemical Corporation 3340 Airport Road Ogden, Utah
RITTER, Darrell Lloyd	U. S. Naval Ordnance Test Station China Lake, California
ROAT, Howard Levi	AC Spark Plug Division, GMC Milwaukee 1, Wisconsin
ROBERTSON, Wilson Bee	Bureau of Naval Weapons Representative Hercules Powder Company Magna, Utah
ROBISON, Gerson H.	Sperry Gyroscope Company Great Neck, New York
ROGERS, Martin W.	Manager, Product Assurance MM&SR RCA Moorestown, New Jersey
RORK, Philip Joseph	QM Research & Engineering Command Kansas Street Natick, Massachusetts
ROSS, Chandler C.	Aerojet-General Corporation Azusa, California
ROTHSTEIN, Arnold A.	AVCO Corporation Wilmington, Massachusetts
ROZETT, Lawrence	Ford Instrument Company 31-10 Thomson Avenue L.I.C., New York
RUMLEY, Darrell Kieth	McClellan Air Force Base California
RUSSELL, Charles Woodrow	Republic Aviation Corporation Farmingdale, New York

NAME	ACTIVITY/INDUSTRY
SADLER, Robert E.	Air Force Communications Service Scott Air Force Base, Illinois
SAMUELSON, Robert Eugene	Motorola Inc., MED/WC 8201 East McDowell Road Scottsdale, Arizona
SARNO, Polo N.	Bell Aerosystems Company P. O. Box 1 Buffalo 5, New York
SCARBOROUGH, Omer George	General Dynamics/Convair 3302 Pacific Highway San Diego, California
SCARLET, Neil Joseph	ARINC Research Corporation 467 Hamilton Avenue Palo Alto, California
SCHAEFER, Earl Homer	North American Aviation Downey, California
SCHMID, Erwin R.	Bell Telephone Laboratory, Inc. 555 Union Boulevard Allentown, Pennsylvania
SCHARFFENBERGER, George T.	Litton Systems, Inc. 336 North Foothill Road Beverly Hills, California
SCHIAVONE, Daniel Charles	Martin Company
SCHIEHSER, George Anthony	Bell Telephone Laboratories, Inc. Whippany Road Whippany, New Jersey
SCHLIE, Walter	Headquarters, USAF The Pentagon Washington, D. C.
SCHRIEVER, Bernard	AFSC Andrews Air Force Base, Maryland
SCHWEITZER, Dean C.	Maxwell Air Force Base, Alabama
SCHWARTZ, R. N.	WSEG OSD Washington, D. C.
SCHWINGE, Heinz T.	U. S. Air Force AFMDO Holloman Air Force Base, New Mexico
SCREEN, Lorin Burton	Department of the Army Washington 25, D. C.
SELDON, Mark Robert	General Dynamics/Astronautics P. O. Box 1128 San Diego 12, California
SENATOR, Frank E.	Operations Research, Inc. 225 Santa Monica Boulevard Santa Monica, California
SEWALL, Richard Murrell	Naval Air Technical Services Facility 5801 Tabor Road Philadelphia 20, Pennsylvania

NAME	ACTIVITY/INDUSTRY
SEYLER, Lesley Leroy	General Atomic Division General Dynamics Corporation P. O. Box 608 San Diego, California
SHAPERO, Albert	Stanford Research Institute 333 Ravenswood Avenue Menlo Park, California
SHARP, Robert G.	Ryan Aero Company Division of Ryan Aero Company Lindbergh Field San Diego 12, California
SHEA, Joseph F.	National Aeronautics & Space Administration Washington, D. C.
SHERIDAN, John P.	Sprague Electric Company 2321 Wisconsin Avenue, N.W. Washington 7, D. C.
SHIELDS, Robert Verdean	CONVAIR, Division of General Dynamics San Diego, California
SHINAFELT, Thomas W.	Aeronautics & Missiles Division Chance Vought Corporation P. O. Box 5907 Dallas, Texas
SHUKEN, Howard Leonard	Space General Corporation 9200 East Flair El Monte, California
SHUPP, Raymond W.	U. S. Naval Ordnance Laboratory Corona, California
SIMONS, Bernard Joseph	General Dynamics/CONVAIR P. O. Box 1952 San Diego 12, California
SIMPSON, Norman Henry	General Dynamics/Fort Worth P. O. Box 748 Fort Worth, Texas
SIMPSON, Paul Kellogg	Sanders Associates, Inc. Nashua, New Hampshire
SIMS, Richard E.	Air Force Unit Post Office Los Angeles 45, California
SMALL, Arnold M.	Hughes Aircraft Company P. O. Box 2097 Fullerton, California
SMILEY, Robert W.	Department of the Navy, Bureau of Naval Weapons Representative SPO, LMSC P. O. Box 504 Sunnyvale, California
SMALL, John G.	California Institute of Technology Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California

NAME	ACTIVITY/INDUSTRY
SMITH, Levering	Special Projects Office Department of the Navy Washington, D. C.
SMITH, M. C.	Headquarters U. S. Air Force Washington, D. C.
SMITH, Raymond A.	Radio Corporation of America Astro-Electronics Division Princeton, New Jersey
SOSDIAN, John P.	U. S. Army Signal Reserve & Dev Laboratory Fort Monmouth, New Jersey
SPANDORFER, Lester M.	Remington Rand Univac Division of Sperry Rand Box 500 Blue Bell, Pennsylvania
SPEER, Ivan E.	AiResearch Manufacturing Company of Arizona 402 South 36th Street Phoenix, Arizona
SPERLING, Philip I.	Office of the Surgeon General Department of the Army Main Navy Building Washington 25, D. C.
SPIEGEL, Joseph	The Mitre Corporation P. O. Box 208 Bedford, Massachusetts
STARK, Edward	Picatinny Arsenal Dover, New Jersey
STATLER, Clifford	Unidynamics Box 231 Marion, Illinois
STEELMAN, Robert J.	U. S. Navy Electronics Laboratory San Diego 52, California
STEEN, Jermone R.	Sylvania Electric Products, Inc. Subsidiary General Telephone & Electronics Corporation 40 Sylvan Road Waltham 54, Massachusetts
STEGENGA, Frederick L.	Douglas Aircraft Company, Inc. 3855 Lakewood Boulevard Long Beach, California
STEIGER, Robert J.	COMPACMISRAN
STEINBERG, Alvin	Army Ordnance Missile Command Redstone Arsenal, Alabama
STEPHENSON, Franklin A.	General Dynamics/CONVAIR P. O. Box 1950 San Diego 12, California

NAME	ACTIVITY/INDUSTRY
STERNBERG, Alexander	Radio Corporation of America Astro-Electronic Products Division Princeton, New Jersey
STERRETT, John K.	DCS/C&E Headquarters, Norad Ent Air Force Base, Colorado
STITCH, Morton	McDonnell Aircraft Corporation St. Louis 66, Missouri
ST JAMES, Louis N.	Bell Telephone Laboratories, Inc. Whippany, New Jersey
ST LAURENT, Paul G.	U. S. Navy Central Torpedo Office Newport, Rhode Island
STOLPER, Edwin F.	Sikorsky Aircraft North Main Street Stratford, Connecticut
STRICH, Robert	Cannon Electric Company 3208 Humboldt Street Los Angeles 31, California
STROPE, Walmer E.	Director of Research Office of Civil Defense Department of Defense Battle Creek, Michigan
STUART, Henry J.	General Dynamics/Electronics 3302 Pacific Highway San Diego, California
STUCKEY, Loyd C.	General Dynamics/CONVAIR San Diego, California
STURTEVANT, Oliver W.	INM LA
SULLIVAN, E. J. MAJ USAF	Headquarters, SBAMA Norton Air Force Base, California
SUMERLIN, William T.	McDonnell Aircraft Corporation P. O. Box 516 St. Louis 66, Missouri
SUSAG, Millins P.	Pratt & Whitney Aircraft 400 Main Street East Hartford, Connecticut
SUTOROWSKI, E.	PW Department NAS North Island San Diego, California
SWEITZER, Harry Frederick, Jr.	Raytheon Company Sudbury, Massachusetts
SWANSON, Douglas William	General Dynamics Corporation
SWIFT, Edward C.	Pratt & Whitney Aircraft 400 Main Street East Hartford, Connecticut
TALL, Max M.	Radio Corporation of America Defense Electronic Products

NAME	ACTIVITY/INDUSTRY
TAYLOR, Richard J.	Aerospace Defense Systems Officer SSD Los Angeles 45, California
TAYLOR, Robert L.	Radio Corporation of America Junction Routes 3 & 62 Burlington, Massachusetts
TERRY, Joseph E.	U. S. Naval Ordnance Laboratory Corona, California
THOMAS, James W.	Vitro Laboratories 1400 Georgia Avenue Silver Spring, Maryland
THOMPSON, David E.	Hercules Powder Company Bacchus Works Magna, Utah
THOMPSON, Francis A	Martin Denver Waterton Plant Denver, Colorado
THORNE, Charles M.	U. S. Naval Torpedo Station Keyport, Washington
THYBONY, William W.	OSD Washington, D. C.
TOBIASSEN, Thoralph J.	ASD Wright Patterson Air Force Base, Ohio
TOMAC, Charles J.	BUWEPSFLTREADREP Pacific NAS North Island San Diego, California
TOWNSEND, Alan R.	Allison Division General Motors Corporation P. O. Box 894 Indianapolis 6, Indiana
TREMAINE, Stanley A.	Deputy Commander, Systems Management Aeronautical Systems Division Wright-Patterson Air Force Base, Ohio
TROXEL, David I.	Radio Corporation of America, Section 416 Reliability & Maintainability Techniques Bldg. 1-6-6 Camden 2, New Jersey
TUPPER, Fred A.	U. S. Army Arty & Msl School Guided Missile Department Fort Sill, Oklahoma
TYDON, Walter	AEROSPACE
TYLER, Charles C.	Western Electric Company 3300 Lexington Road Winston-Salem, North Carolina
TYNDALE, Harold E.	Bureau of Naval Weapons Representative 1100 W. Hollyvale Azusa, California
UDICK, Mitchell L.	Bureau of Naval Weapons Representative Lockheed Burbank, California

NAME	ACTIVITY/INDUSTRY
ULAM, Frederick Anthony	U. S. Naval Missile Center Point Mugu, California
ULANS, Roman Irodian COL, USA	U. S. Army Signal Materiel Support Agency Fort Monmouth, New Jersey
VANDERHAMM, Roland L.	Collins Radio Company 5225 C Avenue N.E. Cedar Rapids, Iowa
VAN TIJN, David E.	ARINC Research Corporation 1700 K Street N.W. Washington, D. C.
VAUGHN, William R.	Atomics International 8900 DeSoto Avenue Canoga Park, California
VERNON, William B.	The Boeing Company Box 3707 Seattle 24, Washington
VIANNEY, Edmond R.	Sikorsky Aircraft Stratford, Connecticut
VICKERY, A. E.	Executive Officer U. S. Naval Air Station, North Island San Diego, California
VIDALE, Marcello Levi	Arthur D. Little, Inc. 35 Acorn Park Cambridge, Massachusetts
VILLERE, Allard C.	General Dynamics Pomona, California
VOGEL, Theodore A.	General Dynamics Pomona, California
VON GUERARD	FMC Corporation 1185 Coleman Avenue Santa Clara, California
WAGNON, Frederick W.	NASA Marshall Space Flight Center Huntsville, Alabama
WALDRON, Stoddard S.	Arthur D. Little, Inc. 1424 - 4th Street Santa Monica, California
WALES, Henry M.	American Bosch Arma Corporation 9460 Wilshire Boulevard Beverly Hills, California
WALKER, Audrin R.	Aeronautical Systems Division Wright-Patterson Air Force Base, Ohio
WANGGAARD, Lars, Jr. CDR, USN	BUWEPSFLTREADREP Pacific NAS North Island San Diego, California
WARNER, William K.	North American Aviation, Inc. Space & Information Division Downey, California

NAME	ACTIVITY/INDUSTRY
WARREN, Robert	U. S. Naval Underwater Ordnance Station Newport, Rhode Island
WEARY, Neil S.	Joint Chiefs of Staff Space & Weapons System Branch The Pentagon Washington, D. C.
WEBER, John Gilbert	U. S. Naval Ordnance Laboratory Corona, California
WEINBERG, Lawrence	Lockheed Propulsion Company Redlands, California
WELK, Horace B., Jr.	U. S. Naval Air Development Center Johnsville, Pennsylvania
WENGER, Floyd E.	Headquarters Air Force Systems Command Andrews Air Force Base, Washington 25, D. C.
WERGEN, James H. COL USAF	Aeronautical Systems Division Wright-Patterson Air Force Base, Ohio
WHITE, Samuel, Jr.	Sikorsky Aircraft North Main Street Stratford, Connecticut
WHITEMAN, Irvin R.	CEIR, Inc. Beverly Hills, California
WILCOX, Allison "J"	Ryan Aeronautical Company Lindbergh Field San Diego 12, California
WILEY, Franklyn Louis	California Computer Products, Inc. 8714 Cleta Street Downey, California
WILLIAMS, Howell Powell	General Dynamics/CONVAIR 3302 Pacific Highway San Diego, California
WILLIS, Galen N.	The Boeing Company 7755 East Marginal Way Seattle, Washington
WILSON, Keith S.	Lockheed-Georgia Company Marietta, Georgia
WINTERS, Harold Melvin	The Technical Material Corporation
WOLMAN, William W.	NASA - GODDARD Greenbelt, Maryland
WOOD, William P.	Martin Company Orlando, Florida
WOODS, Mark W. CAPT USN	OPTEVFOR Norfolk, Virginia
YAZDZIK, Thaddeus R.	Sikorsky Aircraft Stratford, Connecticut

NAME	ACTIVITY/INDUSTRY
YOSK, Earl K.	Defense Supply Agency Washington 25, D. C.
YOST, Harold C.	AC Spark Plug Division GMC Milwaukee 1, Wisconsin
YOUNG, John W.	North American Aviation, Inc. International Airport Los Angeles 9, California
YOUNG, Malcolm A.	International Business Machines Corporation Owego, New York
YOUNG, Paul A	Sperry Utah Company 322 North 2100 West Salt Lake City, Utah
ZAVACK, Nelson	Wyle Laboratories 128 Maryland Street El Segundo, California
ZIER, Harold G.	Army Ordnance Missile Command Redstone Arsenal, Alabama
ZWERLING, Stanley	General Electric Company 3198 Chestnut Street Philadelphia, Pennsylvania

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C. – Price $2.75

☆ U. S. GOVERNMENT PRINTING OFFICE : 1963 O - 682197